

**United States Air Force
Scientific Advisory Board**



Report on

**Why and Whither
Hypersonics Research in the
US Air Force**

**SAB-TR-00-03
December 2000**

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Abstract

This report summarizes the deliberations and conclusions of the 2000 Air Force Scientific Advisory Board (SAB) study on Why and Whither Hypersonics Research in the US Air Force. In this study the committee describes the operational requirements of a hypersonic system and presents a research program for air breathing hypersonics to meet the operational requirements. We define a program resulting in an operational air breathing hypersonic space launch system in about 2025. This program includes several exit ramps and potential options. The exit ramps would lead to either an operational rocket-based reusable launch system or continuation of the expendable course the Air Force is currently on. A Red Team Panel was part of the study team and provides alternatives to the air breathing hypersonic systems to meet the operational requirements. The study results represent an outstanding collaboration between the scientific and operational communities and among government, industry, and academia. The Study committee wishes to thank the many individuals who contributed to the deliberations and the report, as listed in Appendix A. In addition to Scientific Advisory Board members, many ad hoc members devoted their time. The team would also like to thank all the organizations that gave presentations to our panel and hosted us as listed in Appendix D. The Air Force Academy provided outstanding technical writers Capt Susan Hastings, Capt David Jablonski, and Capt Matthew Murdough who provided fantastic support in preparing this report. Lt Col Dan Heale from the Air Force Research Laboratory served as an outstanding executive officer for the Investment Panel as well as provided a liaison role with Air Force Materiel Command.

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The Study committee would like to recognize the SAB Secretariat and support staff, in particular Maj Doug Amon, and the ANSER team, especially Ms Kristin Lynch, who provided invaluable administrative and logistical assistance in pulling together the myriad of inputs into this final report. Their efforts are greatly appreciated.

Finally, this report reflects the collective judgment of the SAB and hence is not to be viewed as the official position of the United States Air Force.



Dr. Ronald P. Fuchs
Study Chairman

September 2000

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Executive Summary

Since the 1960s, the Air Force has had operational hypersonic systems in the form of intercontinental ballistic missiles (ICBMs), launch vehicles, and reentry vehicles. This report addresses another type of hypersonic system, the sustained-flight hypersonic systems characterized by airbreathing hypersonic propulsion systems. The Air Force Scientific Advisory Board (SAB) was asked to assess the operational utility of such systems. To ensure that the usual unbridled enthusiasm the SAB has for new technology did not overwhelm the results, the study incorporated its own red team to identify and assess alternatives. This report is a consensus of the entire study team's recommendations.

While the Air Force has always had enthusiasm for higher speed, airbreathing hypersonic flight efforts have suffered from a series of fits and starts over the past 40 years. During the same time, hypersonic efforts for ICBMs, reentry vehicles, and launch vehicles have prospered. Why is this so? The primary reason is probably that the efforts for airbreathing hypersonics have focused on getting somewhere in less time, and a clear requirement making essential use of such a time advantage has not been established. This has resulted in great difficulty in determining a valid operational concept because

1. The hypersonic system concepts were often complex and took more time to get ready for flight than subsonic systems, thus minimizing the speed advantage.
2. The hypersonic system concepts were usually extremely expensive to develop and acquire, thus calling into question the cost-effectiveness of timely response.
3. The timelines were fragile—that is, for a fixed range, the feasible hypersonic speed region (say Mach 5 to Mach 15) would make a difference only over a narrow window of time relative to that which is possible with high supersonic flight. For instance, as shown in Figure ES-1, for a target at 1,000 nautical miles (nm) there is only a 13-minute window where a reasonable hypersonic speed range would make any difference. If more than 20 minutes time of flight is acceptable, supersonic or subsonic speed is adequate; if less than 7 minutes is needed, Mach numbers higher than 15 would be required.

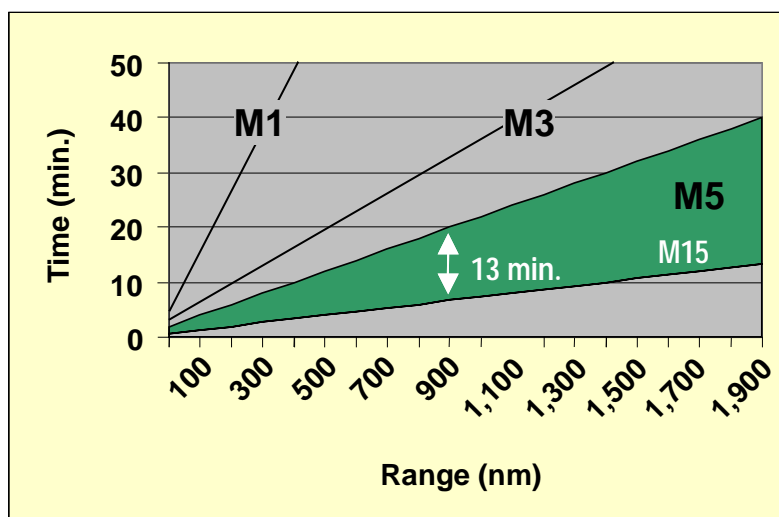


Figure ES-1. Hypersonic Speed Windows

4. Most hypersonic concepts, to take advantage of their fast response, require an intelligence, surveillance, and reconnaissance system that won't exist for a long time.
5. Many argue that the decision timelines are so long relative to the time of flight that there is little need for hypersonic flight. (This argument presumes that the decision timeline can be shortened—there is no clear evidence that this is likely. Interestingly the same argument can be made to support hypersonics—that is, the decision makers want even longer timelines, so shorter times of flight are desirable.)

So, has anything changed? Yes. The greatest change is that hypersonic flight *for other than getting somewhere faster* now appears to be a valid need of the Air Force. The Air Force published *Vision 2020: Global Vigilance, Reach and Power* stating a desire for “controlling and exploiting the full aerospace continuum.” If that vision implies frequent, routine, on-demand operations into and within space, the enabler for this vision is an affordable, responsive, reliable, robust space launch capability. Getting to orbit requires Mach 25 flight—and all speeds between 0 and Mach 25. This interpretation of the vision cannot be fulfilled within the likely Air Force investment program using expendable launch vehicles (ELVs); reusable launch vehicles (RLVs) will be necessary to make routine space operations affordable. Airbreathing hypersonic systems are one of the two concepts that show promise of allowing the realization of these capabilities—the other being rocket systems. On the other hand, if the vision simply implies doing more of the same things done today, the Air Force can probably live with ELVs indefinitely.

What's missing is a clear statement of the mission needs and operational requirements for space control, space warfighting, responsive launch, and other missions that might demand a reusable launch system. This will be a critical enabler for making the Air Force vision a reality, as hypersonics could be the next great step in the transformation of the Air Force into a completely integrated *aerospace* force. We recommend that Air Force Space Command develop appropriate clear statements of its requirements for space launch. These documents must be the basis for steering the investment program as described below. Until these requirements are defined, hypersonic technology programs should be monitored and funded at about their current levels, because these technologies will be required for any resulting program. However, to preclude a continuing slip in the ultimate system availability, a funding wedge for a hypersonic program should be inserted in the budget starting in 2003 or 2004.

When the mission requirements and concept of operations (CONOPS) are defined, key questions will need to be answered before a decision can be made on which technologies will provide an affordable approach to satisfying these requirements. The first question is whether an RLV or expendable launch vehicle is needed. The next is what type of propulsion system should be used. The National Aeronautics and Space Administration (NASA) has been emphasizing a rocket-based single-stage-to-orbit approach that now looks technically risky and might not result in the kind of operational capability the Air Force needs. Two-stage-to-orbit approaches have much lower technical risk, but may be more costly from both acquisition and operational standpoints. The data to make definitive decisions about these key questions and about many more do not exist, nor is there a reasonably paced program in place to provide those data.

While it may seem unreasonable, short of another Apollo or Manhattan Project, we are about 25 years from an operational system enabling routine space operations for the Air Force. Furthermore, this capability is slipping away at almost 1 year per year because current levels of

funding are insufficient to make significant progress. In addition, much of the nation's hypersonic talent is reaching, or has passed, retirement age.

In this report we define a program resulting in an operational airbreathing hypersonic space launch system in about 2025. This program includes several exit ramps and potential options. The exit ramps would lead to either an operational rocket-based reusable launch system or continuation of the expendable course the Air Force is currently on. Early-year investments are those already in the Air Force budget. This program would require annual investments of \$30 million to \$50 million during the latter half of the Six-Year Defense Plan, leading to a moderate-risk decision on a space launch engineering and manufacturing development (EMD) program in 2008. We recommend that this program be executed in partnership with NASA and other government agencies, with adequate Air Force funding to preserve all Air Force-unique requirements. This program should be modified as appropriate when the firm requirements are defined by Air Force Space Command. Figure ES-2 depicts the program with decision points and exit ramps.

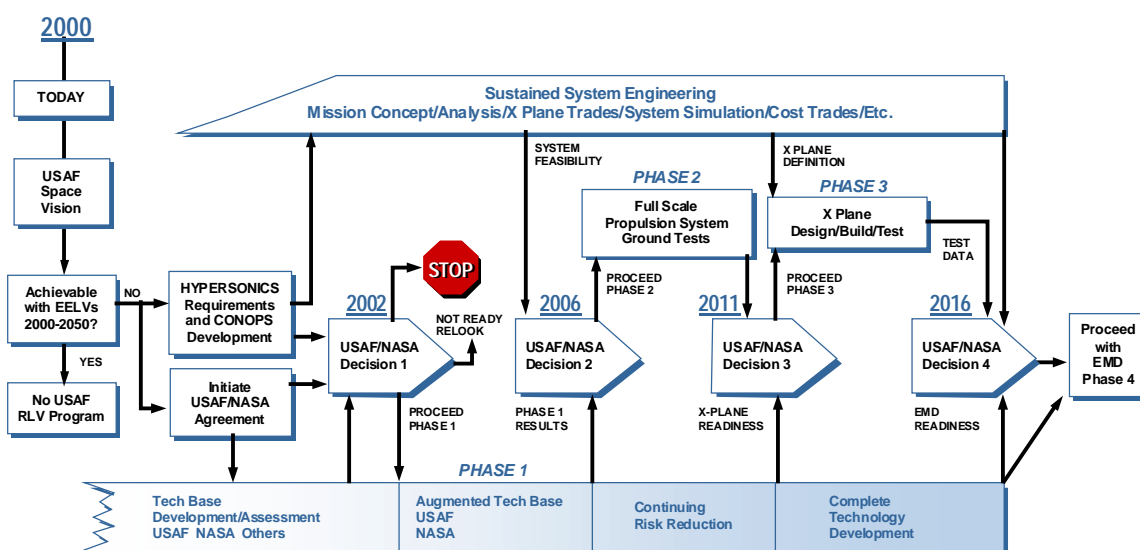


Figure ES-2. *Proposed Program for an Operational Airbreathing Hypersonic Space Launch System*

Several potentially attractive outgrowths will be available during the course of the recommended program. These system concepts do not in themselves justify the entire investment required for an airbreathing hypersonic program, but given that the investment for space launch has been made, their development may be reasonable. Three such concepts have been identified:

1. A long-range hypersonic missile that has shown merit in global wargames
2. An RLV-derived global bomber that provides both long range and fast response
3. A series of technologies drawing on the plasma associated with hypersonic flight to provide high-power directed-energy systems, better aerodynamic performance, and/or survivability enhancements

The recommended program preserves the ability to make future decisions on whether to pursue these concepts. Each of these systems would require an additional development effort in its own right if a decision were made to pursue it.

Many foreign efforts on airbreathing hypersonic flight are under way. There is a risk that these efforts, particularly in Russia, Japan, China, and/or India, could result in a reusable space launch capability that could capture most of the world market—certainly the commercial market. This could have a serious impact on the cost of Air Force expendable launches and could give another nation the capability to threaten our space assets on orbit. The foreign hypersonic missile programs could also indicate an attempt to deny US access to large areas of the world by interdicting our sea lines of communications. In addition, the technology base for plasma applications by aerospace vehicles is most advanced in Russia but is also being pursued in Europe and Japan. The US effort is judged to be significantly behind the Russian effort in many critical areas. Plasma technologies, if their high-risk potential is realized, could lead to even more frightening breakthroughs. The Air Force may need a counter-hypersonics program in the future and, although it is unlikely to be a symmetrical response, it will certainly require a high level of understanding of the foreign systems—a great challenge for a country with a Navy that has to buy foreign supersonic missiles to test its air defense systems because US systems are not capable in that flight envelope.

The red team provided nonhypersonic solutions for each of the applications discussed. The red team also pointed out that the question of the merit of investment in hypersonics is vision related—neither the threat nor economic business cases, with or without shared use, justifies a hypersonic system. The Air Force should both define and execute a program to achieve its vision, or should change its vision. The red team viewpoint has been incorporated into the recommendations and is discussed in more detail within the report.

The need for any Air Force investment in hypersonics depends on the extent and timing of the Air Force vision for extending our aerospace force into the future. “Routine” space operations, responsive launch, significantly higher launch rates, and other factors would dictate an Air Force space launch system that no one is currently developing. We believe that an airbreathing hypersonic space launch is likely to be the enabling element in realizing this vision and that it provides that capability with some interesting spin-offs: access for *global attack*, which would defeat enemy anti-access strategies, and an inherent *aerospace superiority* with directed-energy *precision engagement*. If the Air Force vision of “controlling and exploiting the full aerospace continuum” is to become reality, the Air Force needs a comprehensive plan for hypersonics.

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Chapter 1

Terms of Reference

Air Force Scientific Advisory Board (SAB) 2000 Study on *Why and Whither Hypersonics Research in the US Air Force*

Background: The study will develop a strategy-to-task plan based on operational need for investment in hypersonics, including ground-test facilities. The National Research Council's (NRC's) report on hypersonics provides a good foundation and springboard. The Air Force Research Laboratory (AFRL) generated a technology roadmap that underwrites a propulsion system of Mach 3 and above for three applications: (1) a missile, (2) an air vehicle, and (3) space access. This roadmap also identifies ground-test infrastructure needs, research and development (R&D) being done by other organizations (such as the Defense Advanced Research Projects Agency [DARPA], the National Aeronautics and Space Administration [NASA], and the Navy), and links it to avoid duplication.

Study Products: Briefing to SAF/OS and AF/CC in October 2000. Publish report in December 2000.

Charter: This study will

1. Build on the NRC hypersonics report.
2. Review the AFRL roadmap.
3. Develop operational concepts in both narrative and strategy-to-task formats that require hypersonic speeds (including sustained hypersonic speeds) to enable and underwrite Air Force capabilities to achieve operational objectives (see Secretary Peters' comments).
4. Recommend a time-phased investment plan that is based on operational need and availability technology. This plan will identify key science and technology (S&T) investments, exit criteria, demonstrations necessary for transition to engineering and manufacturing development (EMD) decisions, and considerations for speeds beyond Mach 8.

Secretary of the Air Force F. Whitten Peters Comments:

"I want to make sure the SAB considers our multiweek planning cycles at NCA [National Command Authorities] level and explains why conventional platforms can't perform the national security mission given days and days-to-weeks of truce-to-preposition."

"Please also form a red team to argue the proposition that hypersonics has no military utility, or at least none given costs and available work-arounds."

Study Organization:

Study Chair: Dr. Ronald P. Fuchs

Operational Concepts Panel: VADM David E. Frost, USN (Ret)

Red Team Panel: Mr. Tom McMahan

Investment Program Panel: Dr. Armand J. Chaput

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Chapter 2

History of Hypersonics

2.1 Introduction

For simplicity, this study considers hypersonic flight as flight beyond Mach 5. It has been a reality for the past 51 years, since the upper stage of a two-stage Bumper-WAC research rocket exceeded Mach 5 during a test flight on 24 February 1949 from White Sands, New Mexico. The term *hypersonic* is a translation of the German expression *superschall* (for extreme high-speed flight). Virtually unquestioning expectation that the first flight vehicles into space would be winged, hypersonic designs is implicit in the work and writings of notable pioneers and advocates in the history of rocketry such as Konstantin Tsiolkovski, Hermann Oberth, Robert Goddard, Max Valier, Walter Hohmann, Wernher von Braun, Willy Ley, Chesley Bonestell, and, especially, the husband-wife team of Eugen Sänger and Irene Sänger-Bredt. In fact, however, the time pressures of the rapidly unfolding “space race” between the United States and the Soviet Union resulted in both nations deciding for the more quickly achievable ballistic-missile-lofted blunt-body reentry vehicle option for their man-in-space efforts. This derailed hypersonic spacecraft development so that manned spaceflight, both for the Soviets and the United States, remained the ballistic lofting of tailored blunt-body reentry shapes until the first flight of the Space Shuttle *Columbia* in 1981.

2.2 Background

The United States undertook considerable research on hypersonic aerodynamics for both lifting and ballistic vehicles during the 1950s, typified by the development of specialized ground-test facilities, including hypersonic wind tunnels, arc-jet facilities, impulse tunnels (shock tubes, shock tunnels, and “hotshot” tunnels), and hypervelocity light-gas-gun aeroballistic ranges. While many of these facilities had notable deficiencies (test times measured in milliseconds, high heat losses, and flow contamination problems), they nevertheless were critically important to the development of early ballistic reentry nose cone shapes and the derivation of optimum lifting reentry configurations for both winged and lifting-body design approaches. Complementing such ground-based research methods were flight-test efforts, particularly launches of small multistage rockets from the ground or from research airplanes. By the mid-1950s, hypersonic blunt-body reentry theory had been both theoretically postulated and verified in actual flight-testing using specialized hypersonic reentry test missiles such as the Air Force Lockheed X-17 and the Army Redstone Arsenal Jupiter-C.

The significant developments in rocketry and airbreathing propulsion systems that occurred from mid-century onward greatly influenced the debate over hypersonic vehicle options and missions. The turbojet first flew in 1939; the ramjet in 1940; the high-performance large liquid-fuel rocket engine in 1943; and the practical man-rated reusable throttleable rocket engine in 1960. But these dates serve only as general milestones for numerous other developments, including the supersonic afterburning turbojet, the fanjet engine, turboramjets, supersonic combustion ramjets (scramjets), combined-cycle propulsion systems (rocket or turbine based combined with either ramjets or scramjets), and annular and linear “aerospike” rocket engine technologies. Other than the rocket, the ramjet has had the most direct effect upon hypersonic design. After World War II, American ramjet studies and experiments proliferated. The emergence of the scramjet

propulsion concept, successful ground-test demonstrations of liquid air collection in the early 1960s, and the refinement of the airframe-integrated scramjet concept all sparked great interest in scramjet propulsion for a wide range of hypersonic applications—interest that continues to the present day.

Hypersonic vehicle concepts reflected this maturation in propulsive technology and the technical interests of the times. Initial concepts (for example, the Sänger-Bredt *Silbervögel*) postulated single-stage-to-orbit (SSTO) vehicles based on pure rocket systems, or rocket-lofted boost-gliders (for example, *Dyna-Soar*). By the early 1960s, the maturation of advanced airbreathing technology caused a redirection of thought toward complex, fully reusable two-stage-to-orbit (TSTO) vehicles having airbreathing first stages (with combinations of turbojets, turboramjets, or ramjets-scramjets) and rocket-boosted second stages. The economic realities of the 1970s dictated using semi-expendable approaches, typified by the Space Shuttle. The potentialities of the advanced airbreathing scramjet of the 1980s led to the abortive National Aerospace Plane (NASP) and horizontal takeoff and landing (HOTOL) concepts for airbreathing SSTO vehicles, using complex propulsion systems. The 1990s witnessed less ambitious goals of developing either pure advanced rocket systems (for example, the X-33 and X-34), or technology demonstrators using straightforward scramjet technology (for example, the X-43, also known as the Hyper-X).

2.3 Hypersonic Program Experience

The Sänger-Bredt team developed the first significant vehicle configuration conceptualized for hypersonic flight, the *Silbervögel* of 1938, refined during World War II as a *Raketenbomber* (rocket bomber) concept to undertake antipodal missions using a skip-reentry flight path. This imaginative, if then-impractical, study postulated a sled-launched flat-bottom half-ogive “laundry iron” winged vehicle that would take off horizontally. It would then boost into orbit using a 100-ton-thrust rocket engine operating at an internal engine pressure of 100 atmospheres (atm); in fact, this internal pressure was not met until the development of the Space Shuttle main engine in the late 1970s.

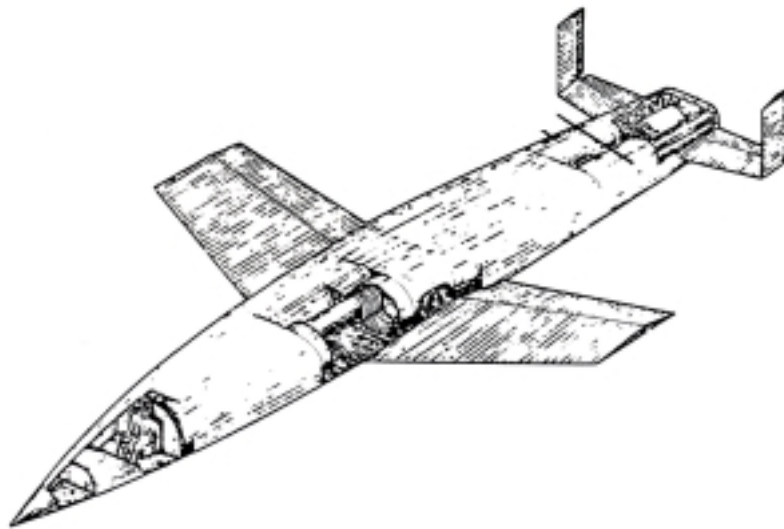


Figure 1. Sänger-Bredt *Silbervögel* Antipodal Aircraft

The merging influences of the Sänger-Bredt report, the experience of the V-2 program, and the emergence of an indigenous American “X-series” research airplane program in the mid-1940s promoted a climate of strong interest in high supersonic and hypersonic flight. Actual flight achievements—notably the first supersonic flight by the XS-1 on 14 October 1947, followed shortly by piloted flights to higher Mach numbers and eventually to Mach 2 (by the D-558-2, 1953) and Mach 3 (by the X-2, 1956)—encouraged this conducive atmosphere.

Early X-series aircraft had concentrated on the problems of transonic and supersonic flight. In 1954, the United States embarked on a joint Air Force–Navy–National Advisory Committee for Aeronautics program for the design and development of a specialized Mach 6+ rocket-propelled air-launched research vehicle. This became the North American X-15, the first “transatmospheric” vehicle (TAV), which reached flight velocities of Mach 6.70 (4,520 miles per hour) and altitudes in excess of 67 miles. Three X-15s were built and flown on 199 flights, air-launched from two modified Boeing B-52 bombers. One was lost in 1967 from a combination of electrical system malfunction, flight control system overloading, and physiologically induced piloting errors. The X-15’s place in hypersonic history is secure, for it was the first airplane to be designed to operate in the transatmosphere and to withstand the thermal challenges of hypersonic flight. Perhaps most important, the X-15 blended the attributes of an airplane and a spacecraft (for example, the plane had three control systems: a sidestick for acceleration into space, a reaction control system for flight at low dynamic pressure, and a conventional flight-control array for descent, approach, and landing).

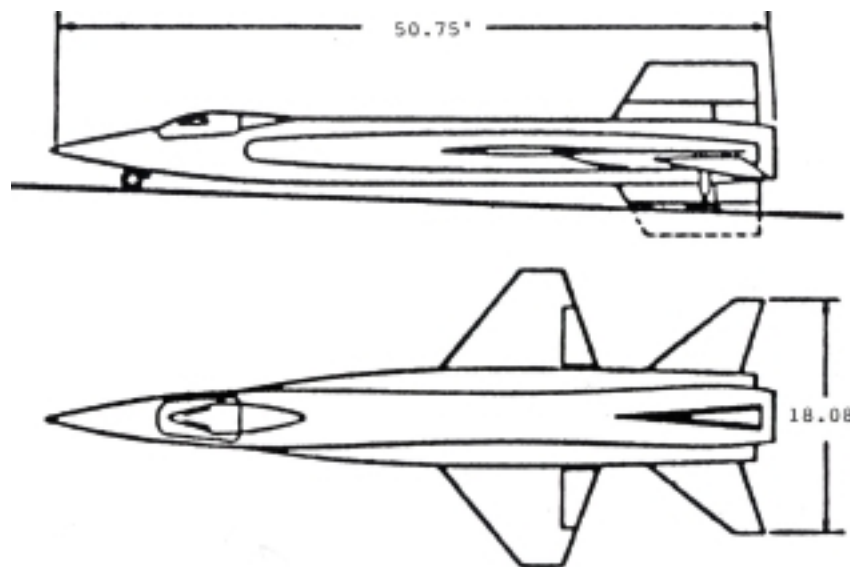


Figure 2. North American X-15 Research Airplane

In 1957, the United States embarked upon an even more ambitious development program for a hypersonic boost-glide vehicle called the *Dyna-Soar* (short for *dynamic-soaring*). After a design competition, the Air Force selected Boeing to develop this flat-bottom radiative-cooled delta-wing vehicle, to be lofted on a growth version of the Titan intercontinental ballistic missile (ICBM). *Dyna-Soar* was a multiphase program, and while proponents hoped it might eventually serve as the basis for a reconnaissance-strike and satellite inspection–satellite interceptor vehicle,

its operational rationale was never well thought out nor strongly accepted by the user community. In fact, confusion over whether *Dyna-Soar*'s role was research or operations was the key reason that the Air Force leadership designated the program "after the fact" as the X-20 in mid-1962. Not helped by its name (*Dyna-Soar* equaled *Dinosaur* in the minds of some post-*Sputnik* space enthusiasts who considered wings anachronistic), this program eventually collapsed, canceled by Secretary of Defense Robert McNamara in 1963, about 2.5 years away from its first flight. The cause of cancellation was far less about technical problems than it was lack of a defined military mission and the desire to replace it with another program—the equally ill-fated Manned Orbiting Laboratory effort. Despite more than 30 years of subsequent work on manned hypersonic concepts, *Dyna-Soar* still possesses the distinction of being the one manned orbital hypersonic program aside from the Shuttle that came closest to achieving actual flight, and its technical contributions were far reaching.

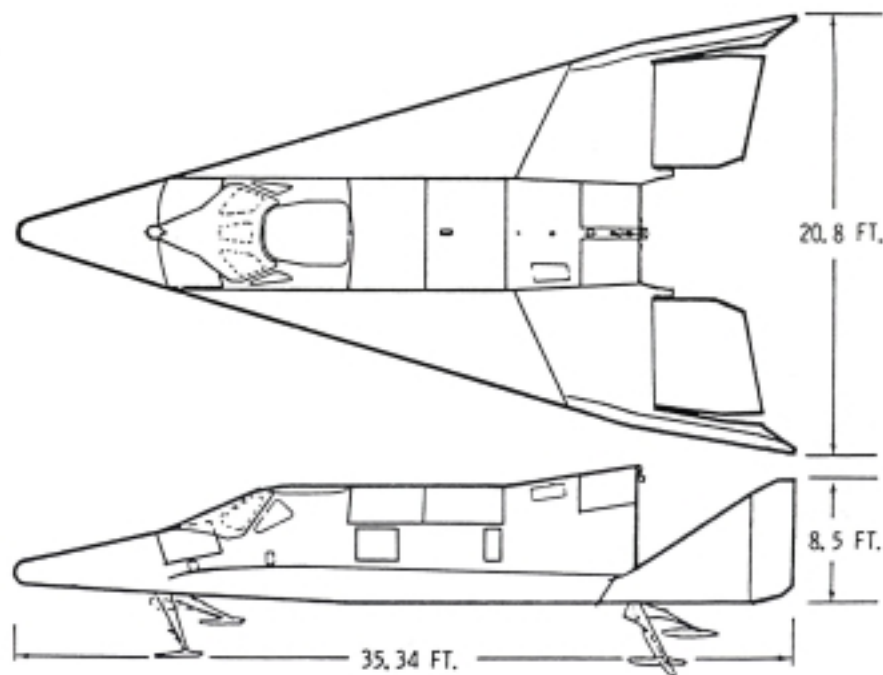


Figure 3. Boeing X-20 Dyna-Soar Boost-Glider

Another abortive program in hypersonics, the Aerospaceplane program, had far less support than *Dyna-Soar*. Aerospaceplane, conceived as an SSTO (and later TSTO) with a complex liquid-air extraction propulsion system, was judged so badly conceived that the SAB's Aerospace Vehicles and Propulsion Panel concluded in October 1963, "The so-called Aerospaceplane program has had such an erratic history, has involved so many clearly infeasible factors, and has been subjected to so much ridicule that from now on this name should be dropped. It is also recommended that the Air Force increase the vigilance that no new program achieves such a difficult position." The Aerospaceplane collapsed for good when no further funds were appropriated in the FY64 defense budget authorization.

In place of these full-size systems, researchers fell back on subscale demonstrators and research craft such as Aerothermodynamic/elastic Structural Systems Environmental Tests (ASSET), an X-20-like radiative-cooled delta-wing reentry shape, blending a flat-bottom glider with a cone-cylinder body flown in 1963–1965; Precision Recovery Including Maneuvering Entry (PRIME), an ablative lifting-body shape, which completed the first maneuvering reentry in 1967; Boost-Glide Reentry Vehicle, an advanced slender cone Mach 18 reentry test vehicle, which successfully demonstrated maneuvering entry over the Western Test Range in 1968; and Sandia Laboratory's SWERV program of a decade later. All of these contributed significantly to the establishment of a hypersonic database for further vehicle and missile design.

From 1963 to 1975, the United States flew a family of subscale piloted low-speed (less than Mach 2) lifting-body demonstrators: the NASA-sponsored M2-F1, M2-F2, M2-F3, and HL-10 and the Air Force–developed X-24A and X-24B. Though not hypersonic craft themselves, these vehicles demonstrated that hypersonic lifting-body configurations could be successfully flown down to a powerless precision approach and runway landing following rocket boost into the upper atmosphere. This offered great encouragement to the Space Shuttle development team, which, on the basis of these results, abandoned the idea of incorporating landing engines in the Shuttle design. But more than this, these lifting-body demonstrators spawned further interest in developing piloted hypersonic demonstrator aircraft. In mid-1976, a variety of Air Force and NASA studies eventually coalesced into a proposed \$200-million development program for a National Hypersonic Flight Research Facility (NHFRF) that could test a variety of modular systems, including airbreathing propulsion concepts, weapons separation, and sensor developments, up to Mach 8. NHFRF collapsed after slightly more than a year later, when NASA determined it could not afford the demonstrator, given its obligations to the Shuttle program. The Air Force, although supportive of the concept, had little choice but to follow suit because it had its own pressing budget concerns.

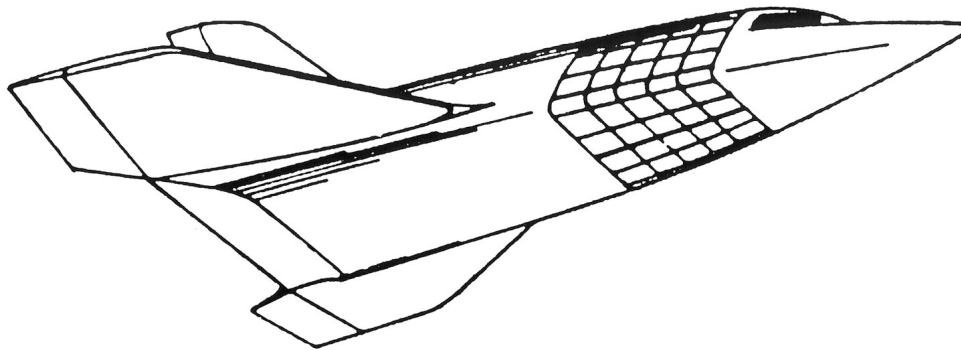


Figure 4. *National Hypersonic Flight Research Facility*

For all its complexity, the Space Shuttle represented a relatively simple approach to spaceflight, being a semi-expendable boost-glider that, like the rocket research airplanes, the X-15, the X-20 concept, and lifting-body demonstrators before it, flew a powerless return to Earth. It was natural that once the Shuttle flew, researchers would recognize the value of using the Shuttle itself for hypersonic studies benefiting potential follow-on vehicle concepts, and, in fact, NASA modified the orbiter *Columbia* with a sensor and instrumentation package to analyze hypersonic

flow around the vehicle during its entry profile down to supersonic speeds. Interestingly, during NASA's painstaking evaluation of potential design configurations for what was initially termed an "Integral Launch and Reentry Vehicle," rocket solutions dominated the evaluation process: airbreathing propulsion appeared only in the form of schemes with "cruise and landing" engines (and the results of the lifting-body program rendered this idea unnecessary). As a result, there was never any serious consideration of complex scramjet or combined-cycle propulsion concepts for the Shuttle. That remained a subject restricted to studies such as the NHFRF and other "paper airplanes."

The 1980s witnessed a tremendous explosion of interest in hypersonics, both in the United States and abroad. In America, the Air Force sponsored imaginative studies for TAVs, and in the mid-1980s, in conjunction with NASA and DARPA, created a joint program office to develop a NASP that was known as the X-30. In Europe, French advocates pursued the *Hermes*, a boost-glider inspired by the American Shuttle, which would use the *Ariane 5* booster; British researchers developed the more technologically demanding HOTOL NASP-like SSTO reusable spacecraft; while the Germans advocated the TSTO *Sänger II*, a hypersonic airbreathing first stage coupled with either a small rocket spaceplane (the *Horus*) or a satellite insertion vehicle.

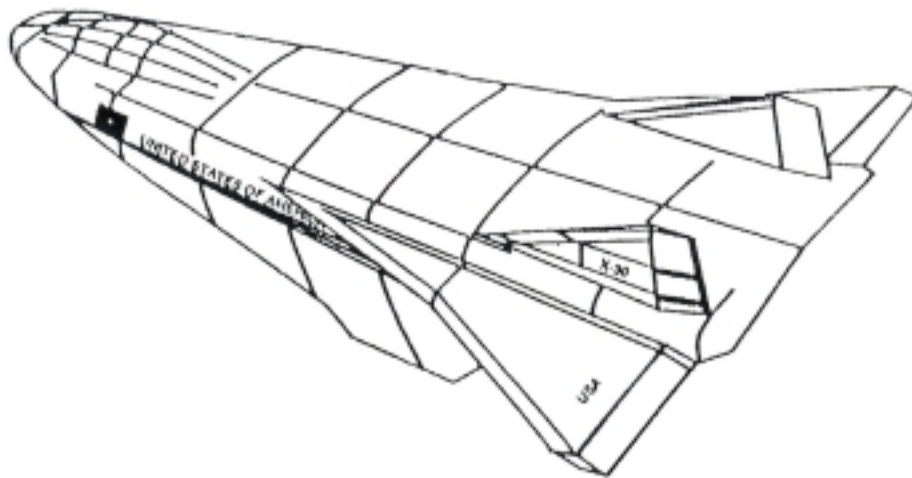


Figure 5. *The X-30 National Aerospace Plane*

NASP resulted in tremendous advances in materials, technology, and mission requirements for hypersonic design, but its overall goal—SSTO routine space access—was far too demanding to be met, particularly when a somewhat arbitrary weight limit of 420,000 to 440,000 lb was imposed. At the end of the program, NASP was fully capable of high hypersonic flight, but faced a deficit of approximately 3,000 feet per second (ft/sec) in attaining orbital velocity. As a result of budgetary drawdown after the collapse of the Soviet empire and the end of the Cold War, NASP support dwindled rapidly, and a series of continuing cuts, coupled with controversy over its mission capabilities and requirements, effectively killed the program in 1993, but it nevertheless continued twitching until 1995. As had happened after the X-20 cancellation three decades earlier, NASP spun off a series of subscale test ideas and programs. Today, a wide range of these demonstrations and others—for example, the X-33, X-34, X-37, X-38, X-40,

X-43, and the Air Force hypersonic technology program—attest to the continuing interest in hypersonics for a variety of civil and military uses.

2.4 Hypersonics: Historical Reflections and Lessons Learned

Today, hypersonics is clearly at a crossroads. Over 50 years of technological investment have brought significant hypersonic capabilities, ranging from launch and reentry systems to the experience of the Shuttle itself. This has been longstanding: nearly 40 years have passed since the first Air Force pilots flew a winged hypersonic craft (the X-15) into space and nearly 20 years since Air Force astronauts first orbited the Earth in the Space Shuttle. But repeated attempts and concepts to develop other large manned hypersonic vehicles for operational purposes have met with disappointment and cancellation, and the path forward is by no means clear or without controversy. This is ironic, for, *at heart, hypersonics represents the fullest integration of the mediums of air and space with the disciplines of aeronautics and astronautics—into genuine aerospace systems that can fulfill the Air Force leadership’s vision of an Air Force that is a genuine Aerospace Force as well.*

This experience offers some important lessons and cautionary notes.

First, hypersonics is consistent with the classic tenets of warfare. More than 2,000 years ago, Sun Tzu wrote, “Rapidity is the essence of war.” Hypersonics offers that advantage, particularly over intercontinental and antipodal distances. In 1945, the great military strategist Major General J.F.C. Fuller noted that the history of weapons development taught that at any particular point in time, a nation had to form its combined tactics around the weapon of the greatest reach. The global-ranging hypersonic vehicle, offering a blend of speed, range, and flexibility unknown to other aerospace systems, particularly missiles, uniquely fulfills Fuller’s perceptive vision. In 1990, the original Air Force *Global Reach—Global Power* strategic planning framework noted that blending speed, range, flexibility, precision, and lethality worked to generate a new national security model subsequently validated by the Gulf War and the military actions and conflicts of the 1990s. Hypersonics offers the promise of extending this American asymmetric advantage through the 21st century as well. Indeed, the need for hypersonics is implicit in the current Air Force strategic planning framework, *Vision 2020*, which stresses that the domain of the Air Force is a “seamless operational medium” from the Earth’s surface to the outer reaches of space, and that the Service must in the future be able to “find, fix, assess, track, target and engage anything of military significance, anywhere...in minutes.”¹

Second, we are already in the midst of the hypersonic era, and have been since the Air Force first fielded hypersonic weapons—the ballistic missile—and hypersonic launch systems nearly 50 years ago. Thus, hypersonics is not a new field. It is not just the stuff of dreams. Rather, it is a field that has had a long history of examination and one that the SAB has generally supported with enthusiasm through the years. Most recently in its *New World Vistas* study of 1995, the SAB concluded, “If the Air Force is to execute faster than an enemy in the

¹ HQ USAF, *Vision 2020: Global Vigilance, Reach and Power* (Washington, DC: USAF, 1999).

21st century, then to reduce time, the only alternative is to go faster. Hypersonic air breathing flight is as natural as supersonic flight.”²

But it might be said that accepting hypersonics as the wave of the future is somewhat like belief in the Second Coming of Christ: one might accept its inevitability, but with little idea when it will actually occur. For example, in the *New World Vistas* study, SAB panel members concluded that by 2005–2010 the Air Force would possess the capability to develop (a) Mach 8 scramjet or ducted-rocket hypersonic cruise missiles capable of hitting hardened targets at Mach 5; (b) Mach 20 boost-glide hypersonic maneuvering reentry vehicles offering Mach 6 terminal impact against buried targets; (c) Mach 8 to Mach 18 scramjet-powered TAVs for force projection, reconnaissance and intelligence, or payload insertion; and (d) a reusable space launch vehicle using either rocket or airbreathing propulsion to deliver up to 25,000 lb into low Earth orbit (LEO) at short notice. Since that study, however, little has been done to fulfill this vision. Thus, the future challenge is to assess the role that the Air Force is to play with regard to this already established—but highly controversial—technological field.

Third, hypersonics today, as a field of inquiry, is at the exact same crossroads that supersonics was more than 50 years ago. History may not be repeating itself, but it surely rhymes. At that time, the United States possessed an inadequate Federal organizational structure for supersonic research. There were serious ground-test facility shortfalls, primarily with wind tunnels. There was inherent risk and design uncertainty. Controversy existed over whether to build piloted or robot research vehicles and whether to make them rocket or airbreathing systems. Defense spending was declining sharply following World War II. Finally, there was no agreed-upon or recognized operational requirement. *But would any reasonable person today say that the United States, and General Hap Arnold and the Air Force in particular, made a “mistake” in supporting supersonic R&D?*

Fourth, hypersonics has always suffered from a pattern of cyclical fits and starts at roughly 15-year intervals. Major programs emerge (such as the X-20, the NHFRF, and the X-30) and are then canceled, typically because of other conflicting needs and overall budgetary pressures. As a rule, dreams of long-range hypersonics fall victim to perceived short-term needs, and even the existence of a favorable defense budget—as was the case in the 1960s and 1980s—is no guarantor of a hypersonic future. The result is that partisans of hypersonics next attempt to operate “on the cheap” with subscale demonstrators (such as ASSET, PRIME, instrumentation packages on the Shuttle, and the Hyper-X). Then these demonstrators themselves form the basis for growing new enthusiasm that fuels interest in the next major program, and the cycle begins again. Given this roughly half-century pattern, it may be anticipated that it will continue in the future as well, with definition of some major program over the next 5 years, and then the next breakpoint occurring around 2008.

Fifth, hypersonics shows surprising resilience given the number of cancellations over time, a tribute to the continuing potential that partisans see for space-access, strike, and reconnaissance missions. These three missions have been the “core” missions envisioned since the first conceptualized hypersonic design, the Sängers-Bredt *Silbervögel*, and they were integral to the one military hypersonic orbital vehicle to come closest to actual test and evaluation, the

² SAB, *New World Vistas: Air and Space Power for the 21st Century* (Washington, DC: SAB, 1995), Summary volume, p. 60.

X-20 *Dyna-Soar*, as well as to the TAV and NASP programs in the 1980s and 1990s. Today, the possibility of linking both manned and unmanned hypersonic vehicle concepts to both of these traditional areas and a range of other military needs, as well as to advanced weapon concepts such as Common Aero Vehicle (CAV) aeroshell dispenser systems and directed-energy (DE) weapons, fuels contemporary interest in possible hypersonic solutions. Again, whether or not a major hypersonic program is initiated in the near future, it may be anticipated that these mission areas will continue indefinitely to be the primary drivers for new hypersonic-based aerospace systems.

Sixth, hypersonics as a field of inquiry has attracted long-standing and near-constant foreign interest. Indeed, the field of hypersonics began not in the United States, but in Europe. Furthermore, some of the more interesting ideas pursued in hypersonics—for example, the hypersonic waverider configuration, or applications of magnetohydrodynamic (MHD) propulsive concepts to hypersonic vehicle design and operations—have stemmed from foreign, not American, work. This foreign interest has always been limited by the necessarily expensive investment that must be made in facilities and resources. It is worth noting, however, that foreign nations have repeatedly pursued development of the same concepts as their American counterparts. Considerable flight-testing of hypersonic-related technology has been accomplished overseas as well, particularly by the Soviet Union prior to 1992 and by the Russian republic since that time. Today, for example, there are well-established, and in some cases extensive, hypersonic R&D investment and testing activities in no fewer than seven foreign countries: France, Germany, Japan, Russia, China, India, and Australia. Foreign hypersonics may offer possible aggressor nations an important means of countering traditional American access strategies; thus this foreign work will require very serious monitoring in the years ahead.

Seventh, hypersonics has suffered from a lack of examination by warfighters of its military utility and practicality. Despite nearly 50 years of Air Force hypersonic studies, and despite clear evidence of great foreign interest in the field, the warfighting community itself has undertaken very little examination of hypersonics. Rather, both operational and technological feasibility has been left to the S&T community. *As a result, hypersonics is at best only loosely fixed in the minds of warfighters, despite increasingly showing potential value in wargaming and simulation to offset and counter a variety of anticipated capabilities a future enemy might be able to employ.* This is significant, for, despite the comparisons with the supersonic breakthrough, *hypersonics is beyond the point where primary questions involve technological feasibility.* Rather, questions now primarily involve investment and resource issues, and issues of operational need—as a group of inquiries, the all-important “Why?” *For these answers, the warfighting community itself needs to assess the anticipated future of aerospace combat and determine whether hypersonics, both manned and unmanned, should play a greater role than it does today.* Then, if the answer is “yes,” the S&T community, to fulfill the vision, can structure a roadmap based on the past half century of accomplishment and thought.

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Chapter 3

Background Issues

3.1 NRC Report Summary

The current hypersonics Summer Study builds on the 1998 NRC study on hypersonics, which was performed at the request of the Air Force. In this study, critical technologies necessary to enable a hypersonic, air-launched, airbreathing, hydrocarbon-fueled missile with speeds to Mach 8 were investigated to determine the feasibility of the initial operation of such a missile by 2015. The Statement of Task (SOT) supplied by the Air Force requests answers to specific questions that logically lead to overall assessment of the existing program and recommendations for future technology investment. To complete the task within the time and resource constraints, the committee focused on the SOT for the duration of the study.

The opening paragraph of the SOT reads:

The examination of the Air Force Hypersonics Technology Program is to concentrate on program strategy and content. The results of the examination will be documented in a study report that will be provided to the Air Force. That report will also contain recommendations concerning possible topics that could be the subjects of investigations of longer-term (2015 and beyond) hypersonics technology applications. The NRC will base its examination on information supplied by the Air Force and other appropriate sources during the course of the study.

This summary paragraph sets the boundaries for the program and solidly focused the committee on the Air Force's Hypersonics Technology (HyTech) Program. When the study began, many committee members assumed that the HyTech program was a component of a broader hypersonics technology investment program. During their first fact-finding meeting, they learned that, due to limited funding, the Air Force had concentrated its resources almost solely on the propulsion system of a representative vehicle and conducted only limited ground-testing of a single Mach 8, hydrocarbon-fueled engine flowpath. Although the committee felt this was a wise decision given the funding constraints, this propulsion concept was not sufficient to accomplish the engine integration required to design a missile system.

Besides propulsion, the five most critical enabling technologies for airbreathing hypersonic missile systems, in order of priority, are (1) airframe and engine thermostructural systems; (2) vehicle integration; (3) stability, guidance and control, navigation, and communications systems; (4) terminal guidance and sensors; and (5) tailored munitions. From the existing maturity of these enabling technologies and the narrow focus of the HyTech program, the committee concluded unanimously in the first meeting that the HyTech program *will not*, by itself, provide the basis for an operational missile system. In order to meet a 2015 initial operational capability, the HyTech program needed broad expansion into all critical technology areas, and system operational requirements needed to be established.

Appendix E contains the specific questions from the SOT and the summary answers provided in the report. Additional excerpts from the detailed answer have been included where warranted.

3.2 National Space Policy

3.2.1 Background

The development of US policy during the past decade was driven by changes required as the result of the *Challenger* accident, the end of the Cold War, and the anticipated increase in commercial utilization of space. There were studies by the Advisory Committee on the Future of the US Space Program (1990) and reports by the National Space Council (1992): *The Future of the US Space Industrial Base*, *The Future of US Space Launch Capability*, and *A Post Cold War Assessment of US Space Policy*. In 1993 there was the NASA Access to Space Study and congressional direction to DoD to study possible ways to reduce the cost of developing and operating military space systems.

3.2.2 The Moorman Study

In April 1994 the Air Force produced the *Space Launch Modernization Plan* (the Moorman Study), which had the goal of investigating all facets of space launch and fostering as much consensus among government agencies as possible. The study covered four options:

- Sustain existing launch systems
- Evolve current expendable launch systems
- Develop a new expendable launch system
- Develop a new reusable launch system

The key findings of the study were, among others, that

- There is consensus on the potential benefits of a new reusable system, but widely divergent views on timing, approach, cost, and risk
- DoD and NASA space launch program coordination needs to be improved

The relevant recommendations were that it was necessary to

- Pursue a cooperative NASA-DoD technology maturation effort that includes experimental flight demonstrations
- Assign DoD the lead role in expendable launch vehicles (ELVs) and NASA the lead in reusables, with these pursuits being self-contained and justified programs, not joint programs
- Maintain top-level DoD-NASA oversight and coordination

In August 1994, President Clinton approved a National Space Transportation Policy making DoD the lead agency for ELV development, and in March 1995, NASA and DoD signed a memorandum of agreement for cooperating on reusable launch vehicles (RLVs).

3.2.3 National Space Policy

In September 1996 the White House National Science and Technology Council (NSTC) promulgated an all-encompassing National Space Policy, which stated that “access to and use of space is central for preserving peace and protecting US national security as well as civil and commercial interests.” It established the NSTC as the principal forum for resolving issues related to national space policy, which was to be implemented within the overall resources and guidance provided by the President.

It provided the following guidelines, among others:

- DoD, as launch agent for both the defense and intelligence sectors, will maintain the capability to evolve and support those space transportation systems, infrastructure, and support activities necessary to meet national security requirements. DoD will be the lead agency for improvement and evolution of the current ELV fleet, including appropriate technology development.
- NASA will work with the private sector to develop flight demonstrators that will support a decision by the end of the decade on development of a next-generation reusable launch system. Technology development and demonstration for the next-generation reusable transportation systems, including operational concepts, will be implemented in cooperation with related activities in the DoD.

3.3 Hypersonic Considerations

The standard definition of hypersonics is *flow in which the Mach number (local flow velocity relative to the vehicle divided by local speed of sound) exceeds five*. On this basis, both airbreathing and rocket-based systems are traditionally classified as *hypersonic* vehicles if they operate above Mach 5. This study will use the term *hypersonics*, unless stated otherwise, to refer to either airbreathing or hybrid airbreathing-rocket vehicles that operate in the hypersonic flow regime.

3.3.1 Operating Ranges of Airbreathing Engines

Among airbreathing engines, the critical speed ranges and potential applications are as follows.

Turbine-based engines including turbojet, turbofan and turbobypass, and turboprop engines and their derivatives can be and are most commonly used in the vehicle range of Mach 0 to Mach 4. Virtually all large aircraft in operation today incorporate turbine-based or modified turbine (for example, turboprop) engines. The technologies associated with gas turbine engines are relatively mature, although there are substantial benefits to be derived from improvements in engine performance and efficiencies, reduction of high-cycle fatigue, and emissions reduction. As a consequence the Air Force has been an active participant in the IHPTET (Integrated High-Performance Turbine Engine Technology) program, along with NASA, industry, and DoD agencies.

Ramjet engines are typically employed in the Mach 3 to 6 flight range. Ramjets are supersonic or hypersonic airbreathing engines in which there are no rotating components (compressors or turbines) and in which the entrance conditions to the combustion chamber are subsonic. Ramjet engines have been used successfully in the context of supersonic missiles. The Air Force and DoD agencies have invested relatively heavily over the past 40 to 50 years in ramjet-related technologies, such as the control of acoustically coupled combustion instabilities.

The scramjet engine is an airbreathing engine without rotating machinery in which the entrance conditions to the combustion chamber are supersonic. Scramjets nominally would operate at Mach numbers exceeding 6. Dual-mode ramjet-scramjet configurations operate over the entire speed range of both the ramjet and the scramjet. The hydrocarbon-fueled scramjet concept explored under the HyTech Program is limited to flight Mach numbers of about 8, which represents the condition at which the fuel-air equivalence ratio required for structural cooling exceeds that required for propulsion at cruise conditions. Scramjets fueled with hydrogen, which have several times the cooling capacity, are not subject to the limitation of Mach 8 flight. The

theoretical specific impulse (I_{sp}) of the hydrogen-fueled scramjet reduces to that of the typical rocket engine in the Mach 20 range. Scramjets have the potential for application in a variety of Air Force vehicles. These applications include a number of alternative space-access concepts, aircraft (for example, strike or reconnaissance), surface- or air-launched missiles, hypersonic penetrator weapons, and hypersonic interceptors.

3.3.2 Generic Concepts

Figure 6 presents the airbreathing flight envelope and several potential hypersonic system applications across the hypersonic speed range of Mach 5 to 25. The hypersonic flight envelope represents the largest flight regime by a factor of approximately 5. Compared to the subsonic, transonic, and supersonic flight regimes, the hypersonic flight regime is the most technically challenging. The lower boundary of the hypersonic flight envelope is determined by heating and material constraints, and the upper boundary, in the case of airbreathing, is constrained by propulsion performance.

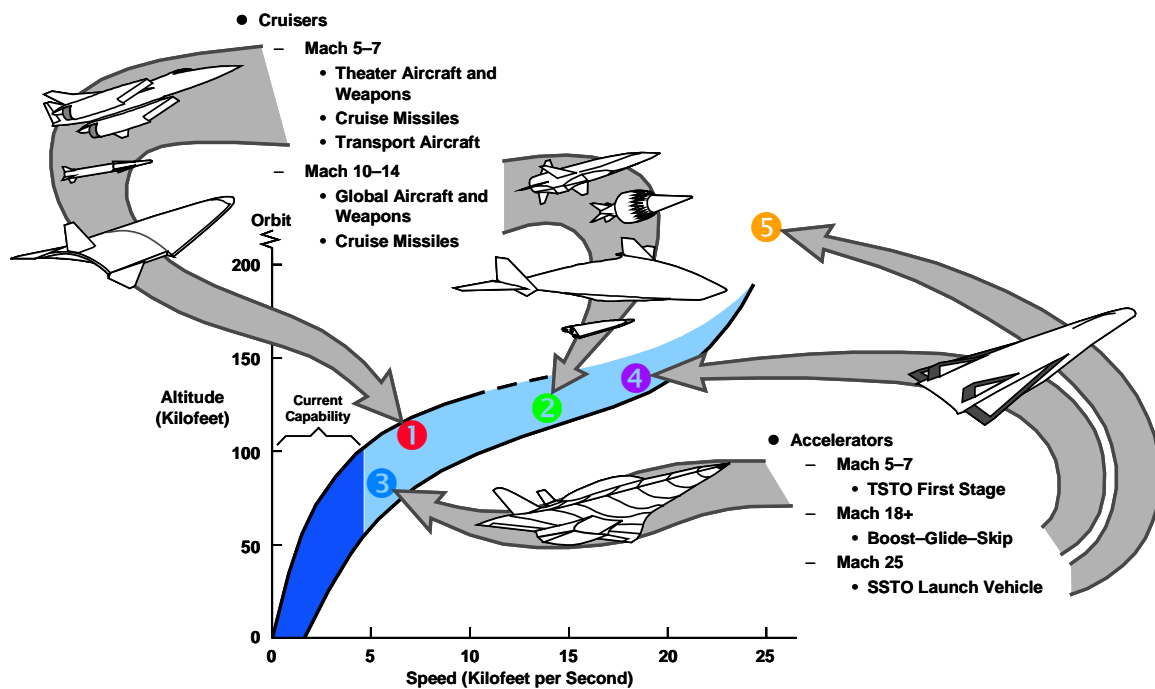


Figure 6. *Hypersonic Generic Concepts Options*

TSTO hydrocarbon-fueled Mach 5 to 7 launch vehicles have been widely investigated by the United States, Germany, France, England, and Japan. Above Mach 10 the fuel of choice for hypersonic systems is hydrogen in liquid, slush, or densified form. Several cruisers with Mach numbers above 10 have been investigated, including both single- and dual-fuel design concepts. A single-stage Mach 23 system has been investigated. It can fly around the world on an unpowered skip-glide trajectory, thus enabling an unrefueled global-range capability. A Mach 25 SSTO design option was investigated extensively by the United States during the NASP program. Other countries have also investigated airbreathing and rocket-powered SSTO design concepts.

3.3.3 Technology Update

We identified a number of interesting technological developments not covered in the NRC and predecessor reports. We discuss them in four categories: propulsion, trajectory optimization, plasma aerodynamics and power generation, and earth penetrators. We also briefly address supportability and maintainability, which have particular impact on future Air Force hypersonic applications and are not receiving much attention as an enabling technology.

3.3.3.1 Propulsion

The development and implementation of robust airbreathing hypersonic vehicles depend on the underlying propulsion concept. Further elaboration on this point will be made in the Technical Recommendations section of this report.

Pulse detonation engines (PDEs) have been receiving significant attention in recent years. The PDE concept is fundamentally different from the traditional airbreathing engine concept (based on the Brayton cycle) in that the PDE combustion process more closely resembles an overall constant-volume “explosion cycle.” The PDE combustion cycle consists of periodic fuel and air (or oxidizer) intake or injection, ignition and propagation of a detonation wave, followed by an expansion wave, and repeated inflow following expansion of combustion products to a reduced pressure. The high-frequency wave reflection at a thrust surface transmits thrust to the vehicle. The PDE’s applications are expected for the flight Mach number range below 5, and this alternative “novel” propulsion concept could, in the long term, be incorporated as a lower-speed component of a hybrid high-speed engine. There is still a great deal of basic as well as development work that needs to be done to establish the PDE as a viable concept.

3.3.3.2 Periodic Optimal Cruise for Airbreathing Hypersonic Vehicles

Unlike conventional atmospheric vehicles, hypersonic vehicles might benefit from nontraditional cruise profiles. Theoretically, it can be shown that the most efficient cruise can involve a cyclic path induced by a potential and kinetic energy interchange. The most important contribution to this cyclic mechanism is the interchange of kinetic energy to potential energy where the flight path goes into a suborbit outside the atmosphere, reducing the drag to zero. When it enters the atmosphere, the engines are started, replacing the energy lost due to atmospheric drag over the cycle. However, other related mechanisms also produce a cyclic fuel-efficient cruise. If the region where the vehicle is aerodynamically efficient is not the same as where it is thrust efficient, then the vehicle may oscillate between the two regions and modulate the thrust of the engine accordingly. A design of a periodic cruise vehicle should be different from waverider cruise vehicles that fly static cruise profile. For example, engine technology may focus on accelerator scramjet development, and the vehicle configuration may be conical rather than a minimum-drag waverider configured for a particular flight condition.

Additional advantages for periodic cruise paths are maneuverability (allowing greater survivability from missile attack), increased stealth, improved communication when outside the atmosphere and no longer in a plasma, and a dramatic decrease in total absorbed heat. Since the vehicle is substantially outside the atmosphere along a suborbit, it can release its weapons or a second-stage vehicle for orbital insertion in a rather benign environment. Furthermore, each time the vehicle enters the atmosphere, a plane change correction using aerodynamic forces can be applied to the suborbit so that mission objectives at the target area can be met. The disadvantages of this concept are the short periods of a high heating rate, the required limits on

the g force in the atmosphere, and the need to turn the engines on and off. Nevertheless, it has been shown that these periodic cruise paths can be mechanized by a closed-loop guidance law that includes the g constraints and retains the optimality of periodic cruise.

Despite the potential benefits of periodic trajectories, they need careful assessment from the system perspective to determine their true benefit.

3.3.3.3 Magnetohydrodynamic/Weakly Ionized Gas (WIG)

For vehicles that fly at hypersonic speeds, it may be possible to extract significant levels of onboard electrical power. The principles of power generation from plasma are well established as the field of MHD. The MHD principle is based on Maxwell's equations in that an electrically conducting medium (that is, the exhaust) flowing through a magnetic field creates an electric current, which has components that are normal to and aligned with the flow. The first MHD device to generate at the megawatt (MW) level for a hypersonic multirole aircraft concept was constructed by A. R. Kantrowitz of Avco Research Laboratory (it was 33 MW). The Air Force did extensive research on MHD generators in subsonic and supersonic regimes from 1960 through 1980, and much of this technology directly relates to a hypersonic vehicle concept.

Significant advances in directed-energy systems have been made. A review of high-power laser and microwave systems is provided in Section 7.2.3.

The use of MHD and the generation of WIGs have been proposed by Russian researchers over the past decade and hold the potential for significant improvement in hypersonic vehicle design. Many of these concepts have been consolidated into a Russian aircraft concept called "AYAKS," which is proposed for flight at high hypersonic speeds (Mach 12 to 14) using hydrocarbon fuels. As illustrated in Figure 7, the novel feature of this vehicle concept is a "plasmamagnetochemical" engine that incorporates a system to generate weakly ionized flow, an MHD power-extraction/flow-deceleration system, a hydrocarbon-fueled scramjet, and an MHD power-addition/flow-acceleration system. Through the synergistic combination of these technologies, along with a steam-kerosene fuel-reforming process that allows balancing of the energy, Russian researchers claim significant vehicle performance improvements relative to aircraft incorporating "conventional" technology.

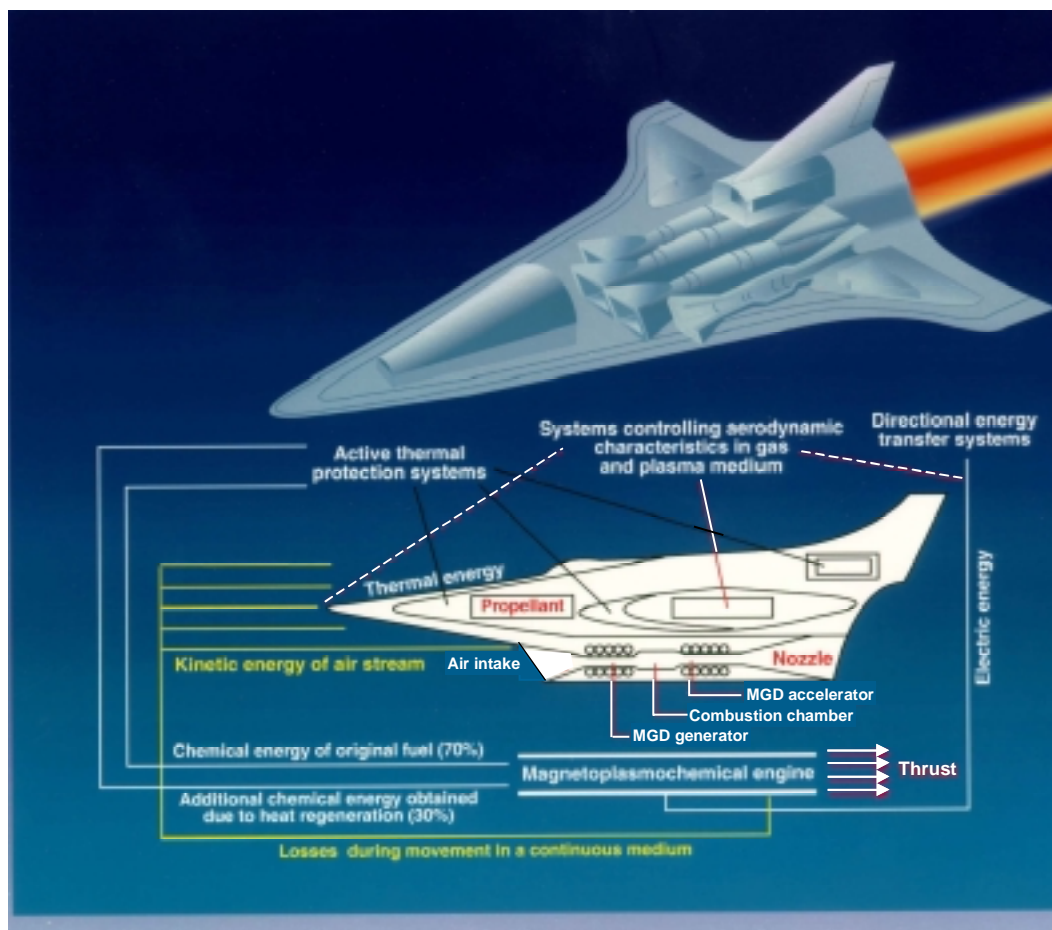


Figure 7. AYAKS Concept Airplane

The generation of a WIG for aerodynamic flowfield modification has been proposed for drag reduction, lift enhancement, boundary-layer separation control, heat transfer reduction, and sonic boom mitigation. The generation of WIGs has also been proposed by Russian researchers for active radar cross section (RCS) control. A WIG with ionization fractions between 10^{-6} and 10^{-5} can be created through electrical discharges between onboard electrodes, electrodeless microwave discharges, direct injection of internally generated plasma, or high-energy e-beam injection. In the process of creating WIGs, spatial and temporal nonuniformities are generated, flow chemistry is excited, and electrostatic and electromagnetic interactions are enabled. Experiments to date have shown drag-reduction potential at energetically efficient power levels for missile-shaped bodies using a high-frequency pulsed discharge to create highly nonuniform flowfields. At present, the fundamental physical mechanisms controlling the interactions are not well understood.

The AYAKS concept incorporates an MHD power-generation system as part of the compression process of the propulsion system. Using the WIG generated on the forebody, the MHD power-extraction system can be used to enhance the inlet capture flow and increase the inlet compression ratio. Using this system, the operating range of a fixed-geometry (or limited variable-geometry) engine may be significantly expanded. Under the sponsorship of the Air

Force Office of Scientific Research (AFOSR), experiments have been conducted at the Ioffe Physico-Technical Institute using rare gases illustrating enormous levels of control of a flowfield through a scramjet inlet. In addition to flow control, the MHD system provides the potential for generation of significant levels of onboard power generation. The energy extracted by this system is used to power the ionization system, with the potential to use the excess to power onboard beam weapons.

Techniques for the generation of WIGs also offer the potential to significantly improve the combustion processes within the scramjet. Ignition of hydrocarbon fuel mixtures and enhancement of the fuel-air mixture may benefit significantly from these technologies, allowing improved performance and greatly enhanced engine operability.

3.3.3.4 Earth Penetrators

A variety of hardened, buried targets is included in the Air Force worldwide target list. The GBU-24 was adequate against hardened aircraft shelters during Desert Storm. However, a new GBU-28 penetrator was quickly fielded to attack deeply buried command and control (C²) targets. More effective penetrator weapons are needed for global power projection. Missile and aircraft storage facilities must be destroyed early in the conflict. Enemy leadership must not be immune from attack on day one of a conflict. Figure 8 is a summary of hardened and buried targets and the weapon options to attack the targets. Only the subsonic and supersonic 2,000- to 4,000-lb weapons plus the nuclear penetrator are available.

Targets

- Conventional weapon storage sites
- Aircraft shelters and caves
- Weapons of mass destruction manufacturing and storage facilities
- Leadership shelters
- Missile storage facilities
- Command and control centers

Penetrator Options

- Subsonic (2,000 to 20,000 lb)
- Supersonic (2,000 to 4,000 lb)
- Hypersonic, KE (3,500 to 20,000 lb)
- Nuclear, supersonic (20,000 lb)

Figure 8. *Buried and Hardened Targets With Weapon Options*

Figure 9 presents, by class, an estimate of the number and depth of the hardened, buried targets contained in the Air Force worldwide target set. In general, as the military importance of a target increases, the number of targets decreases, and the harder and deeper they will be buried. Critical high-priority targets may be located at more than 2,000 ft deep in rock. Current weapons, except the nuclear option, are not capable of destroying these targets.

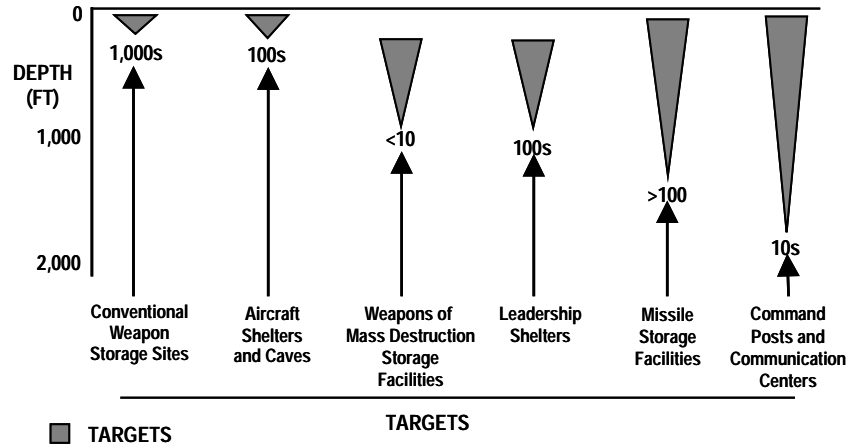


Figure 9. Target Numbers and Depth by Target Classification

The capabilities of the weapon options considered are summarized in Figure 10. The hypersonic speed increases the penetration depth by a factor of 2 compared to current conventional weapons, but increases the targets at risk by only a few percent.

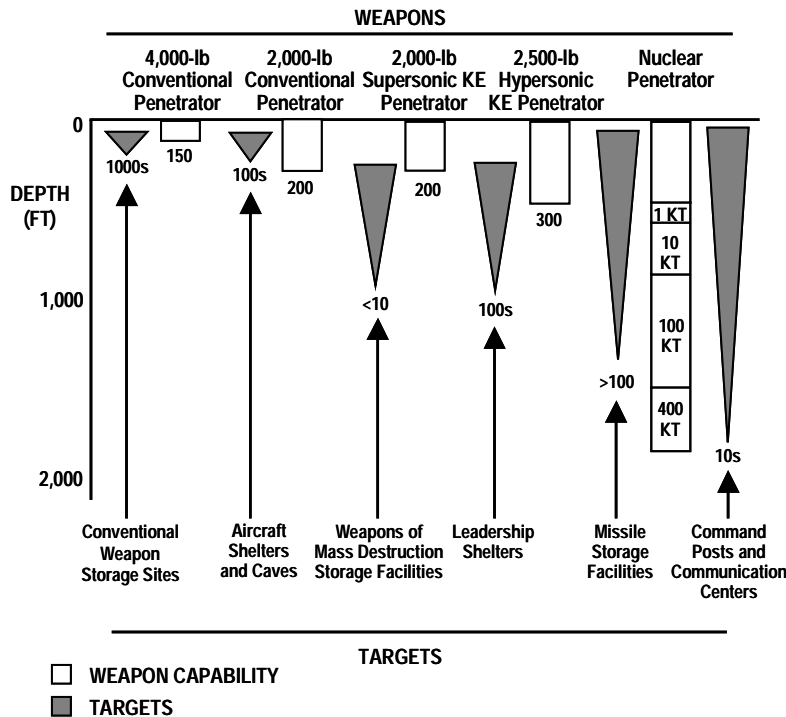


Figure 10. Weapon Capability Comparison

3.3.3.5 Supportability and Maintainability

Only top-level, relatively superficial work has been done in the area of maintainability and supportability. Due to the complexity, high temperature, and high stress of hypersonic solutions,

this area needs major emphasis for potential hypersonic missile, aircraft, and even spacecraft applications. Maintainability and supportability must be incorporated early into the thinking of technologists if there is to be any hope of fielding such hypersonic systems. To a certain extent, the IHPTET program has fundamentally changed the way turbine engines are designed in order to significantly reduce maintenance costs. The same mindset must be applied to hypersonics.

One area of needed research is that of integrated vehicle health monitoring (VHM). Advanced VHM systems could help assure availability of hypersonic systems. A health monitoring system that detects, identifies, and reliably announces a fault with low probability of false and missed alarms is required to reduce maintenance costs. To reduce cost and not increase weight, hardware redundancy should be minimized by the development of redundancy management systems that use analytical relationships to detect and identify sensor, actuator, or part faults.

3.3.4 Hypersonic Expertise: A Vanishing Workforce, a Vanishing Capability

An educated, skilled hypersonic workforce is a cornerstone of future development programs. It is a guard against technological surprise and will ensure that our nation retains its global leadership in hypersonic technologies. Building and maintaining this workforce and gaining crucial experience require a sustained and substantial investment of resources and time. Developing a highly skilled hypersonic workforce is extremely expensive, and today's workforce exists largely because of important but costly space programs. Unfortunately, these highly skilled teams and their research facilities can be disbanded literally overnight, with the accompanying rapid dispersion and loss of capabilities.

The hypersonics workforce is at a crossroads today. The majority of its members will retire in the next 5 to 10 years. Of particular concern is that many of these retiring experts have experimental experience—a characteristic lacking in much of the younger workforce. Furthermore, the hypersonics community has been likened to a guild or trade, in that much of the expertise is passed from the older generation of technologists to younger researchers through practical experience in R&D programs. The pending retirement of much of the experienced workforce is a clear reason for concern.

A focused, coherent R&D program is the best means to ensure that the wealth of experience garnered over the past half century is not lost in the next decade, but rather is transferred to the next generation of hypersonics technologists. It is also the best means to ensure that we do not cyclically relearn lessons from the past or rebuild expertise gained from previous investments in hypersonics R&D.

3.3.4.1 Workforce Composition

Defining the hypersonics workforce in a clear manner is not easy. The development of a hypersonic vehicle requires expertise from numerous disciplines, some very narrowly focused on the hypersonic flight regime and others greater in breadth. Hypersonic technologies, and the associated workforce expertise, can be grouped in four general categories:

- *Hypersonic-specific technologies.* Certain requisite expertise is applicable only to hypersonic vehicles and their flight regime. For example, scramjet inlet design is sufficiently different from inlet design for a traditional subsonic or supersonic fighter aircraft that it is a unique discipline. New areas explicitly applicable to hypersonics, such as plasma aerodynamics to reduce drag and boost hypersonic engine efficiencies, are under active development. High-temperature, high-

strength materials are vital enabling technologies for hypersonic systems. Hypersonic ground-test facilities also fall into this category, particularly given the unique expertise required to design, develop, operate, and maintain such facilities. Development of the necessary knowledge and expertise in these technology areas requires specific study and experience accrued over a period of years.

- *Adaptations of existing technologies.* Other technologies used in vehicle design must be adapted to the severe hypersonic environment. Given that the flight mechanics of hypersonic vehicles are different than those in other regimes, flight control systems must consider the coupling between structures, aerodynamics, and propulsion. Communications, navigation, and other avionics systems must address the effect of the plasma on the reception and transmission of data. Air data systems must be flush with the vehicle body. However, in each example, it is likely that technologies from other flight regimes can be adapted to the hypersonic environment; this is better than creating new and unique disciplines from whole cloth.
- *Integration technologies.* A crucial aspect of hypersonic flight is the combining of structures, aerodynamics, engines, controls, etc., into an integrated whole: the vehicle body is an integral part of the scramjet inlets and exhaust, and plasma flows around the vehicle are highly dependent on the vehicle shape yet have substantial impact on the control mechanisms, to name but two examples. Consequently, experience in vehicle design integration is a crucial skill, unique to the hypersonic flight regime. The loss of personnel experienced in vehicle integration is perhaps the most important issue facing the hypersonic workforce today.
- *Project management of hypersonic vehicle development.* The integrated design, building, and testing of a hypersonic vehicle requires project managers with unique expertise. This expertise is largely due to special aspects of components used in the hypersonic environment and the blending and integration of those components into a vehicle.

3.3.4.2 The Declining Trends in Personnel and Expertise

The early years of space exploration saw large investments in hypersonic technologies. The fledgling space program required applied knowledge of planetary reentry technology for space capsules. Two reentry concepts—the capsule (Apollo) and the spaceplane (*Dyna-Soar*)—competed for the mission to the moon. NASA selected the space capsule with its lower technical risk, but later employed the spaceplane concept in the Shuttle program. The investments of the 1960s produced a large base of specialized hypersonics experts and project managers knowledgeable of the special considerations required to integrate diverse technologies into a hypersonic vehicle. This expertise formed the cornerstone for all subsequent hypersonics programs.

As depicted in Figure 11, the 1960s were the golden decade of space and hypersonics. Since then, hypersonic expertise has been periodic but declining, rising slowly as new programs were funded but dramatically decreasing with budget shortfalls. Furthermore, each peak in personnel has been below previous ones. The Space Shuttle project induced a new period of enthusiasm followed by budget shortfalls. NASP required new technology in terms of airbreathing scramjets and combined-cycle engines, new materials, and a design process in which the disciplines of structures, aerodynamics, and propulsion were highly coupled. Although a vehicle was never built, the NASP program generated considerable new expertise in scramjet technology, computational fluid dynamics (CFD), high-temperature materials, and component testing and evaluation. Some key technical leaders came from earlier aerospace programs, and they helped educate and train new experts in complex hypersonic technologies as well as system integration.

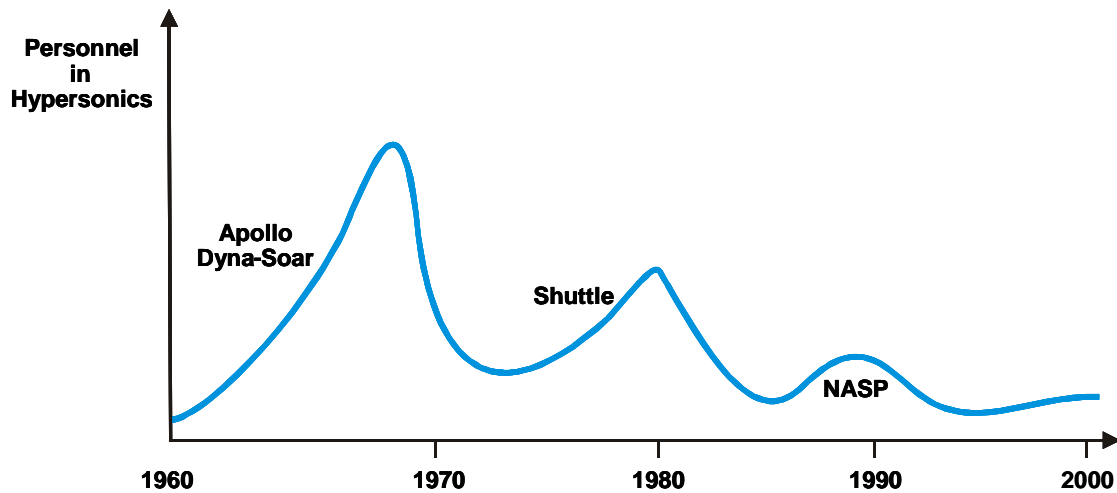


Figure 11. *Sketch of Personnel in Hypersonics Over the Past Four Decades*

The impact of this periodic funding on the current hypersonics workforce size as a function of age is sketched in Figure 12. The dispersion of personnel into other technologies and programs as hypersonic support dwindles is extremely costly, as is the retraining required to meet new hypersonic program demands. Not only are highly experienced personnel lost, but the stigma of a lack of commitment to hypersonics discourages some quality scientists and engineers from entering the field.

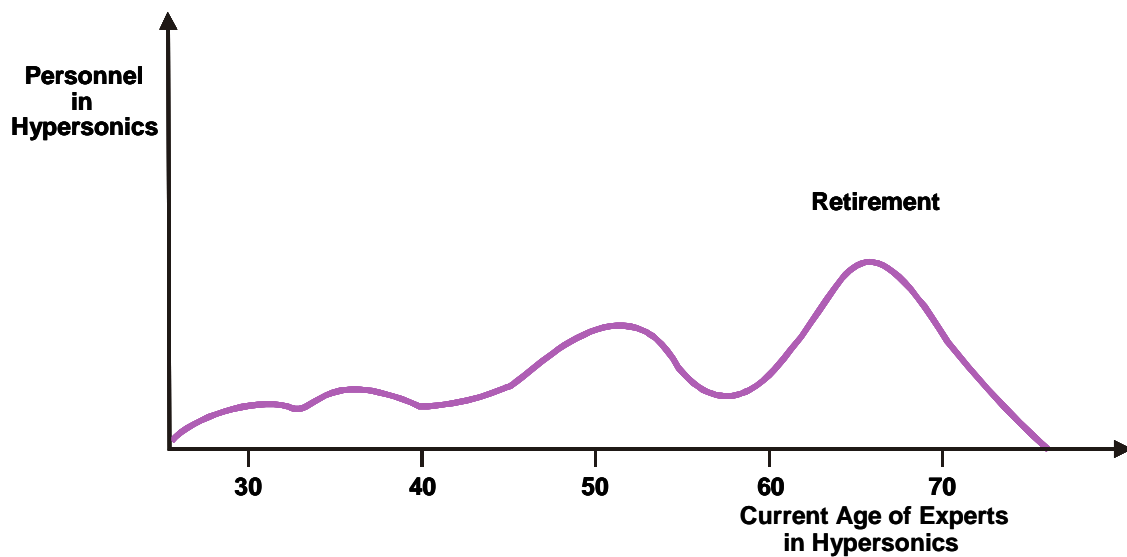


Figure 12. *Notional Sketch of Personnel in Hypersonics as a Function of Age*

An important conclusion from Figures 11 and 12 is that the bulk of the skilled technical workforce, which has matured over the decades and formed the leadership of many programs,

has retired or will soon retire. This loss of expertise is difficult to recover and transfer to the younger generation. Diminishing programs lead to diminishing expertise. Unfortunately, this loss in expertise will be painfully felt if the promise of hypersonics, in terms of an aerospace force, is to be realized.

3.3.4.3 Building and Maintaining New Expertise in Hypersonic Vehicles

Expertise in hypersonics requires an understanding of the difficulties of performing research, development, testing, and evaluation (RDT&E) and acquisition of the hypersonic vehicle system. The only means to maintain existing expertise and to develop new expertise in hypersonic vehicle technologies is through a development program with a sustained funding level sufficient to meet the Air Force's goals.

Hypersonic vehicle design is an immature engineering discipline and can be advanced only by a development program. An airbreathing, hypersonic vehicle system development program will facilitate the transfer of crucial expertise from seasoned experts to younger technologists. Special aspects of hypersonic vehicle design can be transferred through sage direction to the apprentice—the craft and guild model. An important consideration is the development of personnel with expertise in hypersonic systems integration. This expertise has never been fully developed, given that an airbreathing, hypersonic vehicle has never been realized. The expertise obtained in past programs is an important source of lessons learned; however, these lessons were frequently undocumented. A coherent, focused development program is the optimal mechanism for retaining core personnel and ensuring the transfer of costly lessons learned to the next generation.

Finally, the development of an airbreathing, hypersonic vehicle will provide focus to the basic research program. As a consequence, AFOSR will be able to better motivate its research on directed development programs. Not only will this focus foster the development of desirable research expertise, but it will also assist with the education of future hypersonic researchers and development engineers.

3.4 Potential for a Hypersonic Breakthrough or Surprise

Breakthroughs and surprises in hypersonic flight can occur in either technology or hypersonic systems. Systems representative of potential breakthroughs were discussed in Section 3.3.2. Surprises by foreign countries in hypersonics could occur in either technology or systems.

Propulsion, materials and structures, aerodynamics, and fuels are the key enabling generic hypersonic technologies. These technologies separate the hypersonic envelope into discrete design segments based on the range of application of specific choices within each generic technology. Figure 13 represents the range of application of specific technologies for each of the generic technologies selected. For example, turbojets are limited to approximately Mach 4, ramjets are limited to approximately Mach 6, and the limit for operational scramjets has not been determined but is believed to be less than Mach 20. Material selection is a major consideration in the design of a hypersonic system. Above approximately Mach 6, metallic materials must be cooled. Above Mach 6, ceramic material or carbon-carbon is currently required.

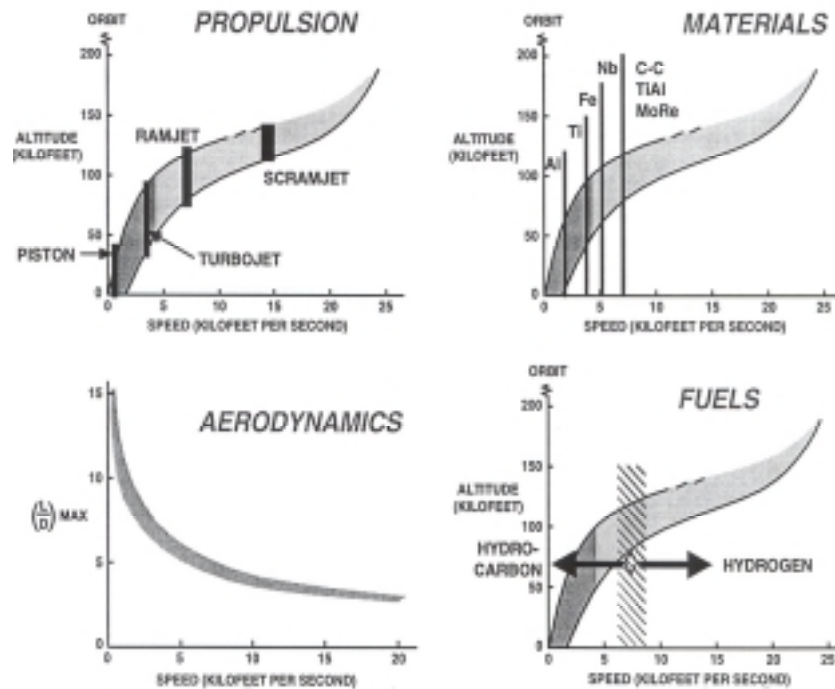


Figure 13. *Technology Applications to Hypersonic Flight*

US efforts in advanced propulsion for reusable space launch applications have focused on airbreathing combined-cycle engines, both rocket based and turbine based, and both hydrogen- and hydrocarbon-fueled scramjets. Either of these advanced engine concepts could make significant changes in the design of RLVs and long-range missiles. Advanced materials include titanium aluminum, alpha, beta, and gamma metal matrix composites; high-temperature engine materials include copper-niobium and molybdenum-rhenium. In addition, work on high-temperature leading-edge material is being investigated at NASA Ames. Extensive work is being done in the United States on hydrocarbon endothermic fuels and densified hydrogen. Computational and ground-test work on high-performance configurations is being done in universities.

The greatest potential for a breakthrough is in propulsion. Current systems and new concepts are limited to specific impulses that require carrying large quantities of fuel, thus implying a large and expensive vehicle. A few ideas exist in basic research which could eventually revolutionize not only hypersonics but all mobile vehicle systems. These opportunities should be explored.

Foreign countries involved in significant hypersonic research at this time include France, Germany, Japan, and Russia. Other countries involved in hypersonics are China, India, Australia, and England. France has been working on a hypersonic antiship missile. The emergence of a hypersonic antiship missile would be of great concern to the US Navy. Russia has an extensive hypersonic research program that includes advanced computation, ground-testing, and flight-testing capabilities. French and US researchers have used Russian flight-test capabilities to conduct low-cost hypersonic flight tests. Russian researchers could at any time achieve a significant breakthrough in hypersonics. Japan has added significant new ground-test

facilities that significantly increase the Japanese ground-test capabilities. Little is known about the Chinese and Indian programs, but work is under way.

3.5 Space-Access Considerations

National Space Policy emphasizes the need for assured access to space. For defense purposes, the principal objective is to have efficient and cost-effective space launch capabilities to carry out the missions of space support, space control, force enhancement, and space force application. The Air Force supports that objective with AFSPC forces committed to USSPACECOM: The Air Force has 90 percent of the forces committed to the Commander-in-Chief, USSPACECOM. Therefore, space access is an inherent Air Force responsibility, which it meets in conducting its assigned space missions.

Physical space access—that is, getting things to, through, and from space—requires hypersonic flight (above Mach 25). As such, the Air Force already employs hypersonic vehicles to get to, through, and from space and has since the earliest days of the space age. Access to space is certain to become more important as more capabilities—and thus greater emphasis—are placed in space. In fact, the stated Air Force strategic planning framework, *Vision 2020*, is to “optimize the great potential of space systems,” “controlling and exploiting the full aerospace continuum,” and “to control space when need be, assuring our ability to capitalize on space’s advantages.” That vision mandates improvements in space-access capabilities; hypersonic investment is consistent with that mandate.

3.5.1 Meeting Air Force Requirements

Today, the only DoD access to space is via expendable systems (ICBMs and ELVs). While the ICBMs generally meet national security requirements for the foreseeable future, today’s space launch systems do not. Assured access to space for national security missions of the future must be responsive, capable, operable, economical, and interoperable. Responsiveness must be measured in terms of hours and minutes, not the days, weeks, and months of today. Advanced spacelift systems must deliver payloads for a variety of missions to space on very short notice. Today, launch systems are tailored to meet specific payloads. Although the evolved expendable launch vehicle (EELV) systems being introduced today will be more capable and operable, they will be limited in their ability to meet launch requirements in 2020 and beyond. The future spacelift systems must be highly efficient, supportable, and maintainable with aircraft-like operational characteristics and attributes. They must operate at significantly lower per-mission and life-cycle costs than current systems. And the advanced spacelift systems must be interoperable with US, allied, NASA, and commercial operations concepts, facilities, and equipment. ELVs, by their very nature, are limited in their ability to meet these criteria. Again, hypersonic investment is consistent with these challenging requirements, particularly for RLVs.

RLVs do provide considerable potential to meet the requirements of future space access. Because they can be designed for aircraft-like operations on Air Force bases, they are inherently more responsive and operable. RLVs could also meet all the lift requirements (such as capacity, standard interface, and simple integration) of DoD users, including employment of such visionary operational systems as the space maneuvering vehicle (SMV) and the CAV. And, because they are reusable, they could certainly be more economical, especially if designed to meet the supportability needs of Air Force operators. NASA clearly recognizes the advantages

of RLVs to enhance access to space and is vigorously pursuing reusable technologies to dramatically reduce the cost and increase the flexibility of space launch. However, NASA is *not* pursuing technologies that are needed to meet Air Force–unique requirements (such as responsiveness and operability).

In summary, space access is an inherent responsibility of the Air Force. That responsibility will increase dramatically as the Air Force transitions further into a true *aerospace* force. All Air Force space access is accomplished via ELVs, which meet today’s requirements but are limited in their ability to meet future demands. RLVs offer immense potential to meet all the requirements of the future US aerospace force. By achieving reusable space access, other applications of the inherent hypersonic technologies involved bring future capabilities to meet other Air Force requirements and to dramatically improve core competencies. To do so requires a vigorous and sustained investment in hypersonics.

Chapter 4

Ongoing Efforts

4.1 Introduction

Within the United States, the Air Force, DARPA, the Navy, the Army Aviation and Missile Command, NASA, and industry are involved in hypersonic research. NASA, with industry support, is developing an X-vehicle to demonstrate a hydrogen-fueled scramjet research aircraft. Hypersonic research and system development is under way in a number of foreign countries, including Russia, China, India, France, Japan, and Germany. The work being conducted under these collective efforts is judged to be extremely competent to the degree that Russia, not the United States, is the technical leader in this field. In the discussion of these foreign activities, space access, weapons, and fundamental technologies will be addressed separately.

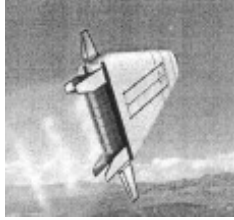
4.1.1 The Air Force

Current Air Force activity on hypersonics systems is shown in Figure 14. Air Force activity on an aerospace plane includes a space operations vehicle (SOV) derived from the NASA RLV program, an SMV derived from the NASA X-37 program, and a Common Aero Vehicle (CAV) derived from previous Air Force maneuvering vehicle programs, a modular insertion stage, and a reusable orbital transfer stage. The SOV has not been defined at this time, even though several concepts have been mentioned and used in AFRL briefings. The AFSPC and AFRL have been spending approximately \$1 million to \$2 million per year on aerospace plane activities. Operations such as the system concept, propulsion, staging Mach number, takeoff mode, basing, and operational concept have not been evaluated. System engineering studies are needed to resolve these issues.

In addition, AFRL has been running a hypersonics technology program called HyTech, which focuses on hydrocarbon scramjet research. The goal of the HyTech Program is to ground-test a hydrocarbon scramjet engine and provide the engine for the DARPA Affordable Rapid Response Missile Demonstrator (ARRMD) program. Between \$7 million and \$15 million per year for the past 5 years has been spent on HyTech. AFRL has also been investing in Russian advanced hypersonics technologies that include WIGs for drag reduction, endothermic hydrocarbon fuels, and scramjet technologies. AFOSR has been focusing on technologies associated with the Russian AYAKS concept. These technologies include WIGs for drag reduction and flow control around a hypersonic aircraft. AFOSR has been spending \$2 million to \$5 million per year on these technologies. Both AFOSR and AFRL have been funding joint research efforts with Russian researchers.

- **RLV**

- **SMV**



- **CAV**



- **Reusable OTV**



Figure 14. *Current Air System Activity in Hypersonics*

NASA and Boeing are building the rocket-powered X-37 (see Figure 15) under a 50-50 cost share agreement. This vehicle will demonstrate technology related to the Air Force SMV and other reentry vehicles. The Air Force is investing approximately \$16 million in X-37-related work.

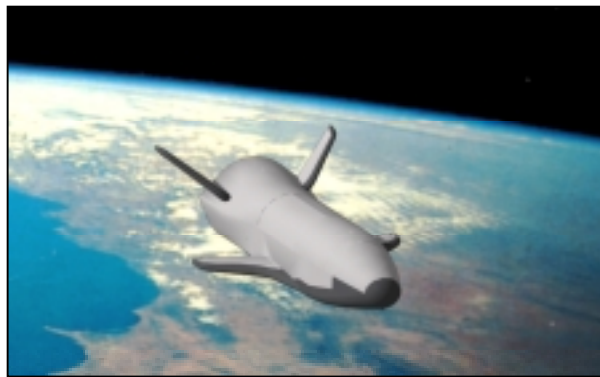


Figure 15. *X-37*

4.2 DARPA (DARPA is considering revising this program.**)**

The DARPA hypersonic standoff missile program is called the ARRMD program. Figure 16 shows potential ARRMD candidates. DARPA has selected the candidate on the right side of Figure 16 as the choice for the demonstration. From the Air Force perspective, the configuration on the right would be better based on a quick look at the load capability of the B-1 and B-2. The objective of this program is to flight-demonstrate a low-cost hypersonic standoff missile. The

goal is to produce an affordable production missile for a large single lot purchase. DARPA has spent approximately \$10 million on Phase 1, an additional \$5 million on a Phase 1A, and plans to spend another \$50 million on six demonstration flights. DARPA intends to use the AFRL hydrocarbon scramjet propulsion system in the demonstration flights. No other engine options are being considered. If the Air Force does not complete the ground demonstration of the hydrocarbon scramjet, a flight test of the DARPA hypersonic missile is in doubt.



Figure 16. *DARPA ARRMD Options*

4.3 The Navy

The Navy is investigating hypersonic aerodynamic, materials and structures, propulsion, and sensor technologies under the Future Naval Capability Time Critical Strike Program, Hypersonic Weapon Technology Program, and the Area and Theater Wide Ballistic Missile Defense system development programs.

The Navy is planning to spend \$292 million over 6 years to develop technologies that will help it detect and destroy time-critical targets (TCT) such as surface-to-air missile (SAM) launchers and mobile ballistic missile sites. The S&T money, which would cover fiscal years 2002–2007, would be spread over 15 projects covering such areas as ground and air sensors, data links, new missiles, and battle management software. The overall goal is the creation of an architecture that allows the Navy to take out high-priority mobile targets in 2 to 10 minutes. Taken together, the projects make up the “time-critical strike” future naval capability, one of 12 such capabilities of the Navy in an effort to make S&T investments more cost-effective. The program is funded at \$49.3 million in FY02; \$67.3 million in FY03; \$66.3 million in FY04; \$48.3 million in FY05; and \$30.3 million in both FY06 and FY07.

As a lead-in to the Time Critical Strike Program, the Office of Naval Research is funding the Hypersonic Weapon Technology Program, which is investigating hypersonic propulsion, aerodynamics, guidance and control, and warhead technologies associated with a Mach 3 to 6 missile launched from aircraft, ships, or submarines.

Hypersonic technologies such as aerodynamics, guidance and control, and sensors are being developed under the Navy Area and Theater Wide Ballistic Missile Defense systems. Many aspects of these technologies are directly related to hypersonic airbreathing missile concepts.

4.4 The Army/BMDO

The Army (Missile Command), in support of BMDO, is conducting the Future Missile Insertion Technology program. Funded at less than \$2 million per year, the program focuses on the development of hypervelocity (less than Mach 10) propulsion technologies through wind-tunnel research of a copy of the Hyper-X Mach 10 flowpath.

4.5 NASA

4.5.1 Hyper-X

The only airbreathing hypersonic X-Plane under development is the NASA Langley Research Center (LaRC) X-43A (see Figure 17). The industry team for this effort consists of Microcraft (prime contractor), GASL, and Boeing. Hyper-X is a \$185-million, 5-year, high-risk, high-payoff technology program to flight-validate at Mach 7 and 10 the performance and operability of an airframe-integrated, dual-mode scramjet and to update or validate Mach 5 through 10 airbreathing hypersonic space launch and cruise design tools and facilities. The program, a joint LaRC and Dryden Flight Research Center effort, will conduct three X-43 flights—two at Mach 7 and one at Mach 10. The first-order success criterion is that each X-43 accelerate under scramjet power after being rocket boosted to the test condition. The first flight is scheduled for February 2001. It will be the first-ever flight of an airframe-integrated scramjet-powered aircraft and will be the fastest flight of an airbreathing aircraft.



Figure 17. *X-43A Vehicle at NASA-Dryden*

NASA is developing plans for a follow-on, fully reusable X-43B (Figure 18) and has study contracts in place with three engine companies (Aerojet, Pratt & Whitney, and Rocketdyne) as well as Microcraft and Boeing. Both rocket-based combined-cycle (RBCC) and turbine-based combined-cycle (TBCC) engine systems are being evaluated.

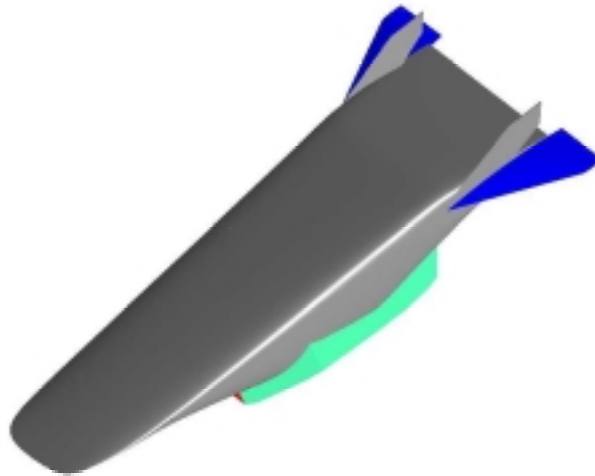


Figure 18. *X-43B Follow-On Candidate*

4.5.2 Third-Generation RLV

The activities led by the Marshall Space Flight Center are directed toward maturing the technologies for a third-generation RLV in the next 25 years. Agency goals for this capability include a 100-fold improvement in safety, \$100 per pound for payload transportation to orbit, and a tenfold improvement in reliability through performance margins that translate to robust design. Third-generation technology drivers include (1) dramatic improvements in propulsion performance, (2) low-drag aerodynamic structures, (3) adaptive intelligent systems, and (4) spaceport range operations. Technology development of airbreathing propulsion options is planned at an annual investment of \$30 to \$40 million. The focus of this program is low-cost, man-rated, scheduled launch. Many, but probably not all, technologies would be appropriate to satisfy Air Force launch requirements. Air Force–unique needs are not being addressed.

4.6 Industry

Industry is participating in hypersonic R&D activities related to space-access, long-range cruise aircraft, missiles, and reentry vehicles. Most of this work is government sponsored, but significant company investments are being made in space access and missiles.

4.6.1 Space Access

The primary activities in space access involve NASA X-Plane programs. Lockheed Martin is developing the X-33 vehicle (see Figure 19), which will demonstrate technology related to rocket-powered RLVs. Rocketdyne is providing a revolutionary liquid oxygen (lox)–hydrogen linear aerospike rocket engine to propel the X-33.



Figure 19. *VentureStar*

Orbital Sciences Corporation is building the X-34 (see Figure 20), which will also advance rocket-powered RLV technology, and the NASA Marshall Space Flight Center is providing its lox-kerosene rocket engine.



Figure 20. *X-34*

In addition to the X-Plane efforts, industry is participating with NASA in the follow-on to the X-43A, and in investigations of second-generation (rocket) and third-generation (airbreathing) RLV concepts.

4.6.2 Long-Range Cruise Aircraft

Industry is working with NASA and the Air Force in the study of Mach 5 to 10 cruise aircraft. These aircraft are being investigated for reconnaissance/strike missions, but could also serve as the first stage of an airbreathing space-access vehicle. Additionally, the Air Force is sponsoring Future Strike Aircraft studies with Boeing, Lockheed Martin, and Northrop Grumman. Under these studies, subsonic, supersonic, and hypersonic alternatives are being investigated as future replacements for today's bombers.

4.6.3 Missiles

The most significant missile activities are DARPA's ARRMD program, the Air Force HyTech Program, and the Navy's High-Speed Weapons Technology program. Boeing is under contract to DARPA for the ARRMD flight demonstration program. Results to date have shown that hypersonic missiles should be no more expensive than subsonic or supersonic alternatives. This is because the engine and airframe for a hypersonic missile can be built with a small number of parts, and low-cost solutions are available for thermal protection. First flight in the ARRMD program is projected for early 2003.

In addition, industry is investing internal R&D funds in proprietary hypersonic missile efforts.

4.6.4 Reentry Vehicles

Boeing and Lockheed Martin have been participating in Air Force-sponsored studies of advanced maneuvering reentry vehicles, often referred to as CAVs (see Figure 21). These vehicles with high lift-to-drag ratios have no primary propulsion, but have movable surfaces to provide high cross-range capability. They are designed to carry conventional weapons (small bombs, submunitions, or penetrators) and can be deployed from conventional ICBMs or a hypersonic cruise vehicle operating at high altitude.

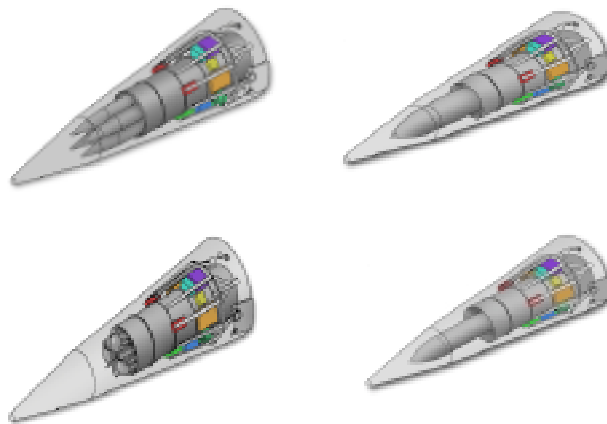


Figure 21. CAV Payload Options

4.7 Academia

Support for hypersonic research in universities is waning. Possibly the largest decrease will come from the end of NASA support for centers of excellence in hypersonics. There appears to be no continuity in this program. NASA does support a few individual researchers, but this investment is sporadic and no longer focused. However, these centers continue to maintain a level of support from industry and DoD.

AFOSR has continued to invest in hypersonics at a constant level (about \$5 million-plus per year). Recently, AFOSR increased its investment in plasma aerodynamics to investigate potential for drag reduction, the control of flow at the inlets and mixing in the combustor using MHD devices, and energy extraction for use in DE weapons. Some investment in Russian technology in the use of WIGs has resulted in establishing an AFOSR research program in plasma aerodynamics.

This new thrust in plasma aerodynamics is complemented by more traditional research endeavors in hypersonics in terms of analysis, computation, and experimentation. Research includes the development of advanced large eddy simulators and direct numerical simulation methods for high-speed viscous, compressible flow over aircraft as well as internal flows in hypersonic scramjet inlet systems. Research in large eddy simulators and direct numerical simulation for the flow near the wall where the turbulence structure becomes small are problems of special focus. Turbulence modeling for rarefied gases is studied through the development of direct simulation Monte Carlo methodology.

Most of the research is performed by individual researchers or small teams in universities in order to resolve novel approaches to the understanding of fundamental mechanisms. The AFOSR budget for funding individual researchers has remained at best constant. There are a few focused research efforts, such as the DoD Air Plasma Ramparts Multi-University Research Initiative. The AFOSR has worked hard to maintain an intellectual presence in hypersonics. The lack of a focus on a development program removes some motivation for the research effort. The decline in NASA and DoD funding does not bode well for enhancing the understanding of fundamental issues and thereby reducing the risk in future hypersonic system development.

4.8 Foreign

Advanced airbreathing space-access technology is being investigated in Russia, Japan, and France and by the European Space Agency. The Oryol hypersonic flight-test program, managed by the Russian Space Agency, focuses on the investigation of hypersonic airbreathing propulsion systems. Two conceptual designs are in work: the TSTO MiG design (MIGAKS) and the Tupolev Tu-2000, an SSTO concept. Both concepts employ horizontal takeoff and landing. To aid in the development of these concepts, Russia can rely on its unparalleled hypersonic ground-test infrastructure for supporting aerodynamic and propulsion development. Russia has also conducted four captive-carry flight tests of a hydrogen-fueled dual-mode scramjet in the Mach 3.5 to 6.5 range using the “Kholod” hypersonic flying laboratory. A second-generation flying testbed, termed IGLA, will expand the tested speed regime to Mach 12 to 14 for investigation of the hypersonic aerodynamic and propulsion environment. In addition to the hypersonic airbreathing engines, Russia has invested heavily in low-speed engines, such as the air-turbo ramjet, which are needed for space-access missions.

A major study of European reusable launch systems has been under way since 1993 under the Future European Space Transportation Investigation Program. The main consensus from the program is that the European RLV will not be an SSTD vehicle.

France has teamed with Russia to investigate a Wide-Range Ramjet engine concept that operates between Mach 3 and 12 using a variable-geometry engine. This program aims at providing a ground-test engine to demonstrate the potential engine performance of an access-to-space vehicle. France and Germany have teamed on the Joint Airbreathing Propulsion for Hypersonic Application Research program, which aims at advancing dual-mode scramjet technology with the ultimate goal of flight-testing a vehicle between Mach 4 and 8.

In Japan, a long-range program aimed at space-access technologies has been in place for the past two decades and continues today with the stated goal of developing a reusable SSTD vehicle with an airbreathing/rocket combined propulsion system. Technology development work includes activity associated with advanced turbo-engines (the Hyper program), combined-cycle engines (ATREX), and dual-mode scramjets. Japan has recently built several large ground-based facilities for investigation of scramjet engine operation at speeds of Mach 3 to 14.

In weapon development, hypersonic research and technology is concentrated on hypersonic cruise missile (rather than aircraft) applications. Russia is the world leader in deploying operational ramjet-powered weapon systems, including the SA-4, SA-6, SN-22, and AS-17. Advanced technology development programs are under way to extend the operating range of ramjet-powered missiles and dual-mode scramjets to Mach 8.

In France, the ramjet-powered missile ASMP is operational in a strategic air-to-ground role. Aerospatiale Matra is also competing for the BVR missile for the Eurofighter with a ramjet-powered air-to-air system. The Promethee missile, which is entering its second phase of development, is a hypersonic air-to-ground system with a cruise speed of Mach 8 and a launch weight of 3,750 lb. Both Aerospatiale and ONERA (Palaiseau) have extensive ramjet-scramjet test facilities staffed with experienced teams.

India and China both possess operational ramjet-powered missiles. Although the two countries are recent entries to the hypersonics field, they are actively exploring scramjet-powered vehicles. India is believed to be developing a high-speed flight vehicle, which will be tested shortly.

The last area to be considered concerns basic research and technology development, which offers the potential for radical improvement in hypersonic system design and performance. The majority of work in this area is being conducted in Russia. Technologies such as plasma aerodynamics and MHD control of flowfields, plasma-assisted combustion, onboard MHD power generation, and plasma-cloaking technologies are all under investigation. Work is under way at the Central Aerohydrodynamic Institute (TsAGI), Central Institute of Aviation Motors (CIAM), and several institutes of the Russian Academy of Science (Ioffe Physico-Technical Institute, High-Temperature Institute, and Moscow Radio Technical Institute) and Universities (Moscow State University and St. Petersburg State University). Although these technologies are relatively immature, they offer the potential to provide revolutionary improvements to vehicle performance in the hypersonic domain.

4.9 Critique of the AFRL Hypersonic Technology Plan

On 18 May 2000, Dr. Lanny A. Jines, AFRL Hypersonic Portfolio Manager, briefed the AFRL Hypersonic Technology Plan to the SAB committee. The stated purpose was to “identify unfunded AFRL hypersonic technology programs that impact Air Force mission capability for Space Operations, Global Reach, and Missiles/Weapons.” The briefing began with a roadmap showing Air Force, NASA, DARPA, and Navy programs, funding for FY95–FY00, and anticipated funding for the DoD agencies for FY01–FY06. The funding summary is provided in Table 1.

Table 1. *Hypersonic Technology Funding Summary (millions of dollars)*

	FY95	FY96	FY97	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06
NASA			28	32	39	41.6	26.1	TBD	TBD	TBD	TBD	TBD
Air Force	10.1	12.6	10	9.3	16.6	16.6	6	6.5	7	7.5	7.8	
DARPA				5.5	5.5	16	24	19				
Navy			0.3	2.7	5.3	8.6	9.7	10.7	8.8			
TOTAL	10.1	12.6	38.3	49.5	66.4	82.8	65.8	36.2	15.8	7.5	7.8	

The Air Force portion of the budget was based on a decision by Secretary of the Air Force Shiel E. Widnall in January 1995 to establish “an aggressive hypersonic technology program funded at a nominal \$20M per year level.” DoD never funded the program to the nominal level. The FY99 funding of \$16.6 million came closest. This level of funding is inadequate to meet the Air Force commitment even with elimination of the in-house technology program. The Air Force funding of \$6 million in FY01 is needed to support the DARPA flight test alone. Furthermore, Air Force funding of \$6.5 million in FY02 through \$7.8 million in FY05 (for a total of \$28.8 million) is still inadequate to begin to answer critical technology questions needed to make rational decisions on potential hypersonic applications. The briefing envisioned decisions being made in FY04 through FY06 on applications of hypersonics to a missile program, a global reach vehicle, and an access-to-space vehicle. Even if NASA were to have primary responsibility for developing either a global reach vehicle or an access-to-space vehicle, the Air Force S&T funding would not adequately address technology issues associated with Air Force–unique requirements to support those decisions. The SAB believes that adding the maximum amount recommended by AFRL (a total of \$25 million from FY02 to FY06) would still be inadequate.

The direction given in Program Budget Decision (PBD) 712 for Aerospace Propulsion Technology for FY02–FY05 funds—that is, the total AFRL budget in hypersonics—lists the following tasks:

1. Modeling and simulation and analyses of combined-cycle engines to identify engine cycles and requirements
2. Proof of concept demonstrations of critical components and engine cycle integration issues
3. Preserve in-house expertise and conduct limited component development
4. Maintain the option for collaborative development with NASA centers

Items 1, 3, and 4 should be executable with the proposed funding. Item 2 could only be superficially addressed with the approved budget. Moreover, little if any of the needed technologies to proceed with weaponizing an ARRMD-type vehicle, in accordance with the 1998 NRC Report guidance, are included in the direction.

Top-level charts were also presented that listed the technical challenges and identified the organizations that presumably are addressing some of these challenges. Challenges were identified in vehicle integration, munitions, flight controls, terminal guidance, avionics, and propulsion. There was little, if any, evidence that the current AFRL program was addressing these challenges.

The remainder of the brief was devoted to describing recommended technology options for “plus ups” of the PBD 712 funding by \$3 million, \$4 million, and \$5 million per year in FY02–FY06. The Directorates of AFRL were asked to submit proposed tasks, which were then categorized by application, namely Space Access, Global Reach Aircraft, and Missile. A “rack and stack” with assigned numerical values was made and the totals were used as the basis of selection. We believe there was a fundamental flaw in this approach. A topic that was pertinent to only one of the three applications would be unlikely to compete successfully with a topic pertinent to all three applications. An example is the technology required to develop a TBCC engine, which would be primarily of interest for the Global Reach Aircraft category. Another example is the Level I Plan. The 5-year plan contains three programs, \$4.52 million for advanced Ceramic Composites, \$6.27 million for Vehicle Health Monitoring and Non-Destructive Evaluation Flight Operations, and \$1 million for High-Speed Air Breathing Propulsion (Hydrocarbon) for a total of \$11.79 million. Considering that candidate conceptual designs for space access and global reach aircraft don’t even exist, we find it difficult to believe that we should spend 53 percent of the budget on health monitoring.

We contrast this approach to the well-organized planning and execution of the hypersonic technology program within the Propulsion Directorate of AFRL. This program has provided the engine flowpath, including extensive direct-connect and freejet test data, characterization of the endothermic fuels, and development of actively cooled combustor panel sections for the DARPA-funded AARMD flight-test program. This work has been closely coordinated with an in-house technology program highlighted by tests of generic injector-combustor concepts in direct-connect test apparatus. An extremely valuable database has been generated regarding flame stability in wall cavities, ignition limits, and combustion efficiencies of several candidate fuels, and documentation of combustor-inlet interactions in isolator sections. These efforts are complemented by a very strong effort in CFD analysis of dual-mode ramjet-scrumjet flowpaths.

Similar planning and leadership have been characteristic of the portions of IHPTET and IHPRT managed by the Propulsion Directorate. It will be prudent to apply this approach to the broader-based program in hypersonics that will involve several other AFRL directorates. Astute management of the program will depend on the development of a rational procedure to identify the key technology shortfalls, a method for prioritization, and a means for responsibly allocating available resources to successfully resolve these issues. Of course all of this presumes a clear understanding of what the Air Force requirements are or might be.

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Chapter 5

Potential Military Utility of Hypersonics

5.1 Introduction

Vision 2020, the Air Force's strategic planning framework, states that the Service is an "integrated aerospace force. Our domain stretches from the earth's surface to the outer reaches of space in a seamless operational medium." Furthermore, it commits the Service to a future in which "we'll provide the ability to find, fix, assess, track, target and engage anything of military significance, anywhere...in minutes."

In reality, the Air Force is limited to atmospheric operations below an effective altitude of 80,000 ft and to operations in Earth orbit. The vast reaches of the transatmosphere³—over a full 85-mile band above the Earth—remain beyond the ability of the Air Force to exploit for any operations. Furthermore, the Air Force is limited in the speed with which it responds to national needs. Air units deploy at approximately Mach 0.75 from the continental United States (CONUS) with fighters, bombers, tankers, airlifters, ISR assets, etc. Or, they deploy at speeds above Mach 18 with nuclear-tipped ICBMs. There is no in-between option.

We evaluated a number of possible military applications for hypersonics. These are discussed below. Our deliberations began by reviewing the definitions of hypersonic flight, examining powered as well as unpowered hypersonics, rocket as well as airbreathing propulsion, and a full family of enabling technologies. We next examined the potential operational benefits of hypersonic velocities across a broad mission array to postulate and assess various applications.

The primary, compelling application of hypersonics for Air Force missions is space access. That is an enduring, critical mission requirement for the Air Force of today and even more so for the Air Force described in *Vision 2020*. Routine, reliable, flexible, and supportable space access is key to the aerospace force of the future.

Beyond space access, a number of hypersonic applications have considerable military utility. These include a long-range, hypersonic aircraft with potential for truly global reach and strike capabilities; hypersonic missile applications to address a range of targets, including time-critical and hardened targets; and "spinoff" benefits involving exploitation of unique hypersonic MHD power generation for improved aerodynamic and propulsive advantage as well as for possible weapon and survivability applications.

In summary, hypersonics offers the promise of a unique set of capabilities and attributes that can dramatically expand and improve Air Force core competencies and mission execution. Hypersonic speeds enable true global reach in a matter of minutes to a few hours, attack of critical targets from standoff ranges in minutes, and the opportunity to operate in, and dominate, the entire aerospace continuum—the powerful objective of the Air Force vision.

³ Altitudes from 80,000 ft to low Earth orbit (roughly 100 miles).

5.2 Space Access

Airbreathing hypersonics offers the Air Force a revolutionary path to maintain aerospace dominance throughout the 21st century. The primary motivation for the Air Force to invest in hypersonics is to assure aerospace superiority against a future peer competitor. To provide this assurance, space launch costs must be reduced substantially, and the ability to launch responsively must be achieved. Only by developing these capabilities can the Air Force evolve to a state at which it can realize space dominance and effectively apply systems such as the SOV, SMV, space-based laser (SBL), and space-based radar (SBR). A comparison of the Air Force *2020 Vision* with current realities is provided in Figure 22.

- | | |
|---|---|
| <ul style="list-style-type: none">▪ Current Air Force Aerospace Vision<ul style="list-style-type: none">▪ Control space when need be▪ Capitalize on space advantages▪ Engage anything of military importance anywhere, and to ...▪ Engage within minutes, not hours▪ Achieve desired effects from any chosen range▪ Strike from CONUS▪ Improve stand-off capability | <ul style="list-style-type: none">▪ Current Realities<ul style="list-style-type: none">▪ Air Force does not have transatmospheric access, operations, or dominance capability▪ Air Force can not engage anywhere within minutes except by ICBMs▪ Space sortie rate will be cost limited using EELVs▪ Response capability limited with subsonic cruise missiles |
|---|---|

An airbreathing RLV could provide increased launch affordability and future sortie capability

Figure 22. *Air Force 2020 Vision versus Realities*

The future needs of the Air Force are synergistic with those of NASA and industry (see Figure 23). NASA is striving to provide low-cost servicing of the Space Station and to provide safe human access to space. Industry, on the other hand, is striving to create new markets, which also involve safe but affordable human access to space. To fully achieve Air Force, NASA, and industry objectives, launch costs must be reduced to about a hundred dollars per pound, and flight safety and reliability must be increased to levels approaching those of today's airliners. It is possible that these goals will be achieved only by developing airbreathing RLVs. Because of the higher performance and lower mass fraction,⁴ airbreathing RLVs offer the promise of greater robustness and safety than rocket-powered RLVs. Therefore, they should afford lower operating costs.

⁴ AFRL-PR-WP-TR-2000-2114, *Hypersonic Applications and Technologies for USAF*, July 2000.

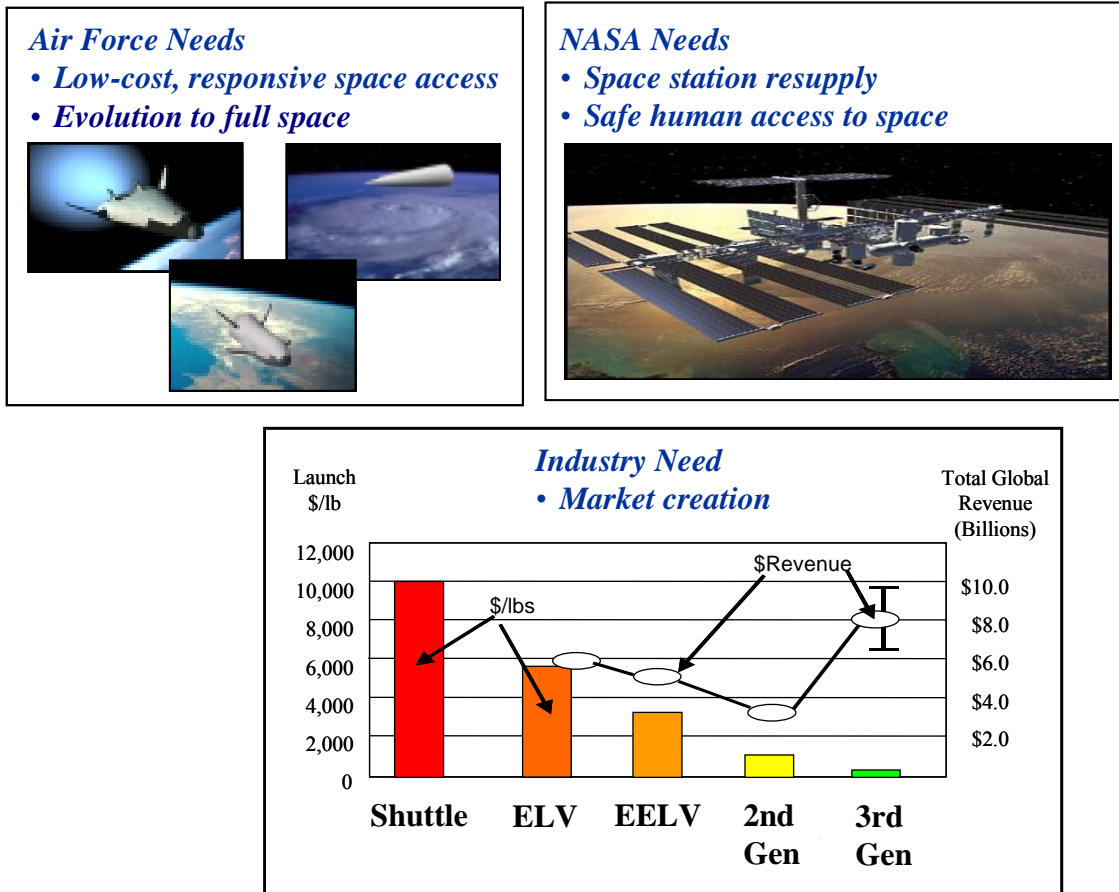


Figure 23. Assured Space Access: Stakeholder Perspectives

Airbreathing RLVs could provide the Air Force with a means to enhance all six of its core competencies: aerospace superiority, information superiority, global attack, precision engagement, rapid global mobility, and agile combat support. For example, low-cost, responsive space access for SMV, SBL, SBR, and command, control, communications, computers, and intelligence, surveillance, and reconnaissance (C⁴ISR) could be achieved by a two-stage, multirole, airbreathing RLV. One or even both stages of this launch vehicle could have long-range cruise capability and thus enable prompt, global attack missions from CONUS using precision weapons. During emergencies, these same stages could provide rapid global delivery of critical supplies and personnel, augmenting conventional transport aircraft. Finally, technology developed for airbreathing space access could be spun off to enable fast-reaction, standoff missiles. As such, airbreathing RLVs offer the promise to greatly enhance the future security and economic well being of our nation.

Three different two-stage, airbreathing RLV concepts are shown in Figure 24 to illustrate the range of options. (Other options are examined in the Billig report *Hypersonic Applications and Technologies for USAF*.⁵) Option A of Figure 24 has a staging Mach number of 4 to 5. The first stage, which is powered by hydrocarbon-fueled turboramjet engines, can be employed with the second stage for space-access missions, or by itself as a future strike aircraft. The second stage

⁵ AFRL-PR-WP-TR-2000-2114, *Hypersonic Applications and Technologies for USAF*, July 2000.

is powered with lox–hydrogen rockets or RBCC engines. If RBCC engines are used, this stage can also be deployed for global attack missions using CAVs or DE weapons, without the need to go into orbit.

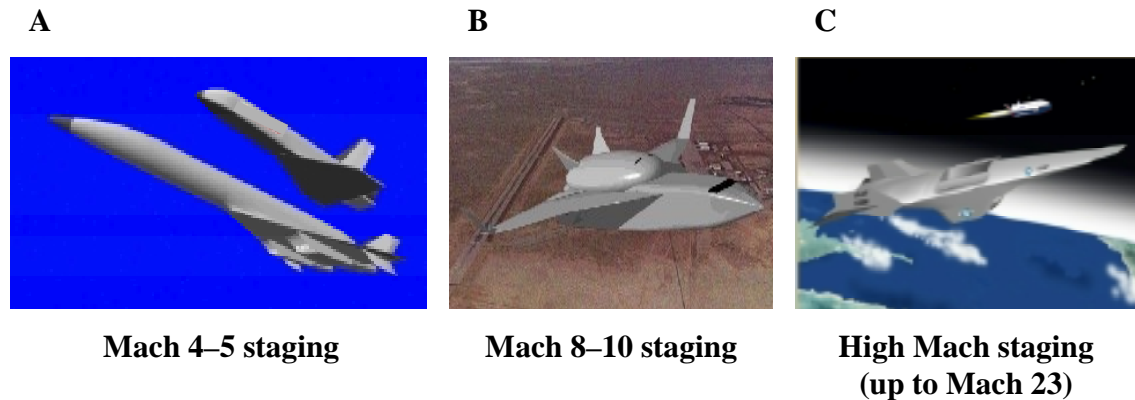


Figure 24. *Airbreathing Reusable Launch Vehicle Concepts*

Option B has a staging Mach number of 8 or 10. For Mach 8 staging, the first stage would be powered by a hydrocarbon-fueled TBCC engine system. This system has hydrocarbon-fueled turboramjet engines and hydrocarbon-fueled dual-mode ramjet-scamjet engines in an over-and-under arrangement, with the turboramjet engines on top. (RBCC engines, in place of the ramjet-scamjets, or an auxiliary rocket system could be employed to perform a pop-up maneuver to permit low-q staging.) For Mach 10 staging, the engine arrangement would be similar, except that the dual-mode ramjet-scamjet, or RBCC engines, would be hydrogen fueled. In both cases, the second stage would be powered by rocket engines with lox-hydrogen or lox-hydrocarbon propellants. Unlike Option A, however, only the first stage of this option would be employed for global attack missions, in which the vehicle would be refueled during the return leg of the trip.

Option C has a staging Mach number of up to 23, which is close to orbital velocity. The first stage could have similar engines to those in Option B (Mach 10 first stage), but would have the capability to fly around the world unrefueled.

All three example options have the potential for the low operating costs, responsiveness, and safety to satisfy the Air Force *2020 Vision*, which requires far greater launch rates and operating tempos than needed today. System-level trade studies would be required to select the best option for development.

5.3 Missiles

Potential Airborne Hypersonic Missile (AHM) operational attributes include

- Increased range
- Significantly reduced time to target
- Increased missile and aircraft survivability
- Increased cost-effectiveness by reducing required support to aircraft for a given strike mission

- Propulsion options that include solid-rocket and airbreathing engines
- Production costs that should be similar to those for subsonic missiles for either approach (based on ARRMD program study results)
- Development risk that is higher for an airbreather than it is for a rocket
- Increased kinetic effects of impact
- Exploitation in the battlespace of a new regime (altitude, speed, etc.) that could provide significant asymmetric advantage

5.3.1 Surface Attack

Long-range, high-speed, air-to-surface missiles can have significant military utility, provided that targeting information is available to exploit their inherent advantages.

Standoff systems have clearly demonstrated the value of long-range systems, which do not put military aircraft and personnel at risk. For example, standoff capability is provided today by various subsonic cruise missiles. Experience in the Kosovo operation demonstrated the ability to update targeting during the B-2 flights from CONUS, which expedited the process of attacking a target. This improvement in the targeting process is of great advantage to a military commander trying to strike critical targets. In fact, any improvement in the process, from target identification to actual strike, is an advantage to a military commander.

Some would argue that the delays of the current C⁴ISR systems are so long that the additional improvement in times of weapon flight, from subsonic to hypersonic, have little effect on the overall result. This argument fails to recognize targeting as a *process* involving many steps. The process begins with target detection, recognition, and identification; then proceeds through the decision-making steps: assignment of weapon, means of attack, unit to conduct the attack; planning; actual employment; weapons engagement; and actual strike. Improvement in any portion of the process can benefit the military commander. There are certainly opportunities to improve the C⁴ISR system as a significant portion of the process. These improvements are a top priority in the Air Force today, and we can expect major advances in the next 10 to 20 years. But that does not mean opportunities to improve the rest of the process should be overlooked. And, as improvements in the C⁴ISR process are realized, the role of hypersonic attack may become even more advantageous, giving the commander the opportunity to rapidly strike important targets well before they can impact operations.

As an example of hypersonic missile applications against a TCT, Figure 25 presents a future notional timeline for the deployment of a theater ballistic missile (TBM). Also shown is the AHM reaction time and time of flight, assuming a circa 2020 C⁴ISR system that can search and identify the TBM in a few minutes as it moves out of hiding. The AHM requirement is to engage the TBM *before* it launches.

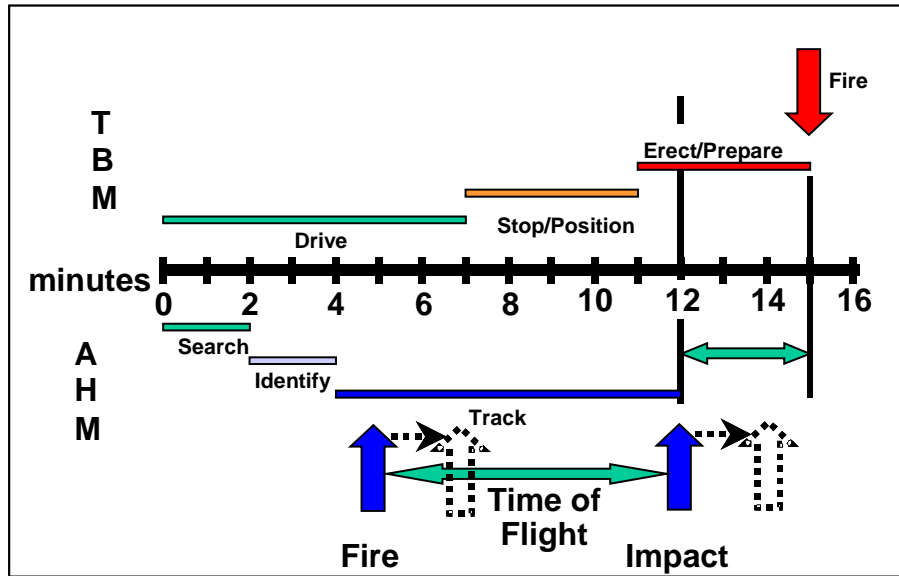


Figure 25. Notional Deployment Launch Timelines for TBM and Associated AHM

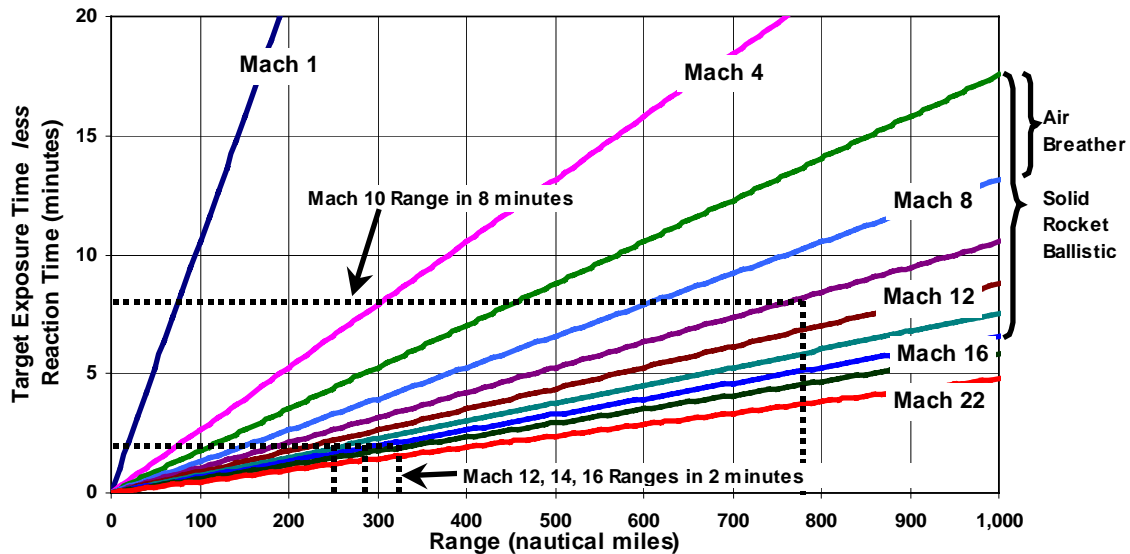


Figure 26. Hypersonic Missile Ranges versus Exposure Times for Various Mach Numbers

Figure 26 shows that standoff ranges of 500 nautical miles (nm) and the target exposure time of less than 5 minutes drive the AHM speed to be hypersonic. Subsonic cruise missiles are unable to respond in less than 20 to 30 minutes at standoff ranges of 200 nm and are thus not viable today or in the future for TCTs.

TCTs drive high speed, but once a high-speed missile is in the inventory, it could be used against any ground target. Since it appears possible that production cost for the same quantity of missiles could be comparable for either subsonic cruise or hypersonic flight (as shown by the ARRMD program), development of hypersonic missiles should not necessarily wait for the C⁴ISR community to solve the time-critical case.

These missiles can fly two trajectories. For airbreathers, an atmospheric flight path is required to provide the oxygen for propulsion. This path requires the missile to stay in the atmosphere and encounter the environments of heat and drag. Ballistic trajectories alleviate these problems by traversing the atmosphere (as quickly as possible) both on exit and reentry. Highly reliable, well-developed, solid-fuel rocket technology is available for this trajectory.

Reentry is at about one-half the velocity of ICBMs, so today's reentry vehicle technology can easily be relaxed and scaled down to the Mach 12 to 14 reentry speed of a ballistic AHM.

The operating concept is depicted in Figure 27. It shows that a 168-inch missile, 20 inches in diameter, and weighing around 2,250 pounds can be carried by all current and programmed combat aircraft. The F-15E, B-52, and B-2 have longer bays and can carry a 3,500-lb missile, 20 inches in diameter, and 250 inches long. The range and load-carrying capacity of the bombers are very attractive for long-range missions from CONUS or from limited remote airfields around the world.

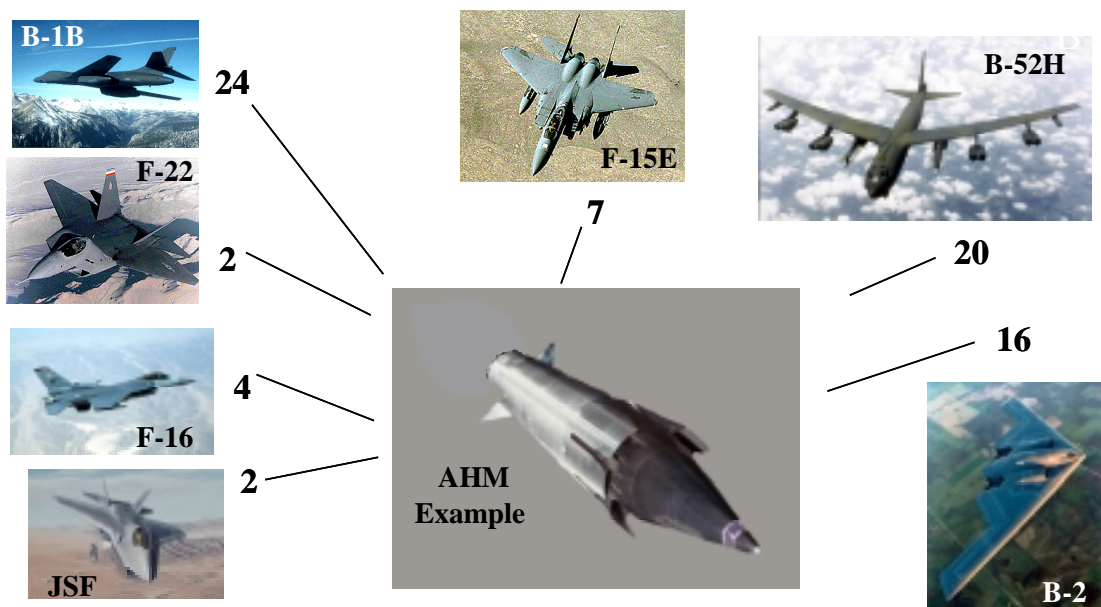


Figure 27. *Air-to-Surface Hypersonic Missile and Launch Aircraft*

The size and speed of an AHM operating off the fighter aircraft provide the air commander with a forward-deployed force that has the flexibility of optimizing munitions to various battle situations. The AHM would open a new regime in the battlespace (range, speed, etc.) that provides the commander increased options.

Airbreathing AHMs using hydrocarbon fuel with uncooled combustion chambers have a top speed of Mach 6, which can be increased to Mach 8 with endothermic cooling of the combustion chamber. The range depends on the propellant mass, but the 168-inch AHM will travel 600 nm and can be throttled to a lower speed for greater range. In addition, a 250-inch version, operating from the F-15E, B-52H, or B-2, would have a longer range, assuming that the thermal problem associated with longer, high-speed flight can be resolved.

The fact that missile production costs are driven by quantity and guidance opens up major cost-effectiveness advantages. For stationary, well-defended targets, the ability to stand off in sanctuary and yet maintain a high rhythm of battle has a high payoff in some scenarios as demonstrated in Air Force wargames. Given that production costs are comparable for subsonic and hypersonic missiles, it seems reasonable that advantages of speed would be desired by the battlefield commander. Thus, the first-generation AHM could be for stationary targets, with growth to add seekers or respond to moving targets with instantaneous C⁴ISR and target updates to the AHM while in flight.

5.3.2 Air to Air

An air-to-air version of the 168-inch AHM might be assembled by exchanging the surface attack Maneuvering Reentry Vehicle with a derivative of the US Army Theater High-Altitude Area Defense (THAAD) program's Kinetic Kill Vehicle (KKV).

The THAAD KKV currently weighs 32 kg (70 lb) and operates in both the atmosphere and in space. The high dynamic pressure design point for THAAD is 4 km/sec at a 21-km altitude. The air-to-air AHMs fly entirely different trajectories from THAAD KKV's, and they are thermally much less stressful.

Significant synergy could accrue to the Air Force by developing the AHM air-launched solid-fuel rocket propulsion and exploiting BMDO's investment in KKV technology.

The air-to-air AHM could also provide TBM kill from any Air Force aircraft because the 168-inch AHM fits on any of them. Thus the benefits of aircraft mobility are exploited and new aircraft are not required. Another major benefit occurs because the KKV physically impacts the TBM unitary warhead, resulting in one or both of the following:

- Physical destruction of nuclear payloads
- Physical destruction of chemical and biological containers in the low vacuum of space, thus killing biological agents or spreading chemicals over great volumes and rendering them ineffective

In contrast, physical destruction of the TBM booster will result only in the shortfall of a fully operable payload, be it nuclear, chemical, or biological, with full effectiveness wherever on the ground it happens to fall.

The air-to-air AHM has two or more times the speed of TBMs, and therefore it has a huge head-on kinematic range against TBMs, but it also has significant kinematic tail-chase capability.

Figure 28 shows the large kinematic launch footprint covering the TBM from launch to reentry down to an altitude of 50 km.

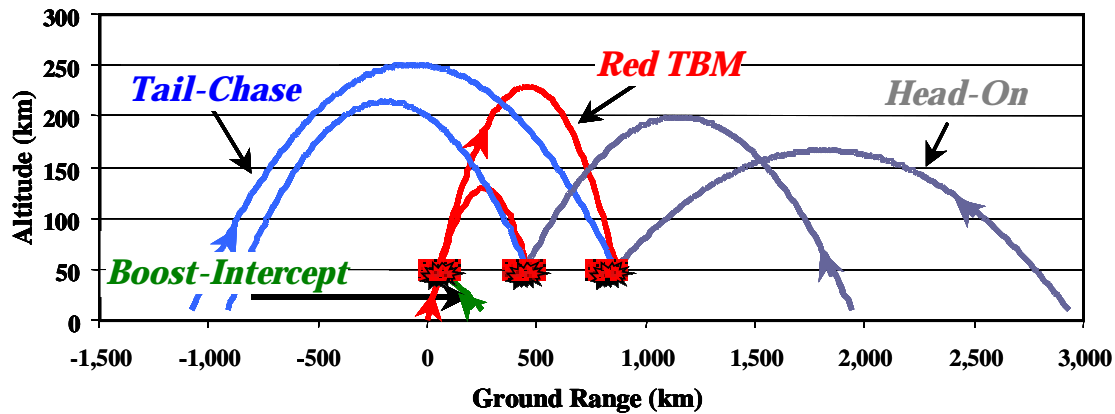


Figure 28. AHM Kinematic Performance and TBMs

Figure 29 shows that the air-to-air AHM combat space against TBMs is above the clouds. Therefore electro-optical (E/O) target detection, tracking, and communications systems are directly applicable. Advanced Low-Altitude Navigation and Targeting Infrared for Night and airborne laser (ABL) acquisition technology are available with better resolution, electronic countermeasures capability, and smaller volume and weight than a radar system.

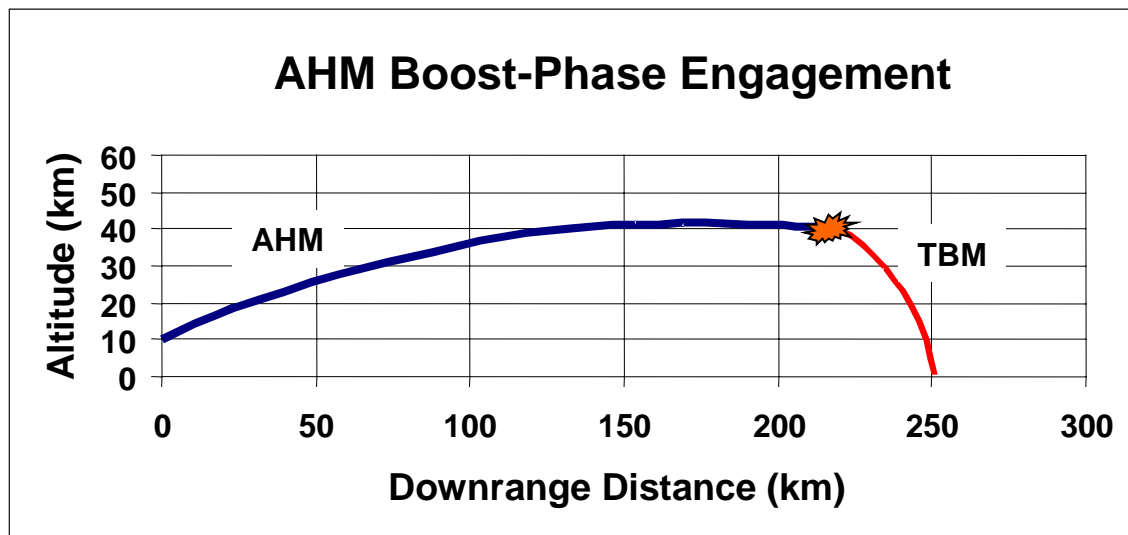


Figure 29. Boost-Phase Engagement

Data obtained with Aerospace Corporation engineers through the Air Force ABI system program office in 1995 indicate that an E/O sensor could be used for air-to-air AHM targeting. For a sensor at a 10 km altitude, the acquisition range increased during the boost phase as the TBM climbed to higher altitude with increased atmospheric transmissibility. Medium-wave collecting optics between 0.4 inch and 8.0 inches in diameter provide acquisition ranges in the 600-km range during boost, and an 8-inch medium-wave infrared search-and-track capability is around 800 km even after boost.

These data provide technical feasibility and confidence that a useful E/O sensor system can be designed to operate on the air-to-air AHM launching aircraft. A fighter may need to carry a pod with optics on both ends for 360° coverage, but bombers should have adequate volume for installing these relatively small E/O systems.

The line of sight from the launch aircraft to the KKV is above the clouds. Therefore, a separate low-power laser will be the best communication link to a beacon transponder on the KKV. Thus the launch aircraft would control the KKV during flight. Offboard sensor target data will be sent to the launching aircraft and will update the KKV as appropriate. In general, operating conditions for the air-to-air AHM are less stressing than for the THAAD application, so the transfer to a different first- and second-stage booster would require minimal modifications. A longer time of flight for the air-to-air AHM will probably require larger thruster fuel tanks and batteries. A low-power laser communication transponder and receiver are also needed.

The AHM exploits a new battlespace regime (altitude, speed, range, etc.) that will offer an asymmetric force advantage to the Air Force. It is important to recognize that the recurring cost for these missiles is comparable (in the same cost range for production quantity) to the cost of subsonic cruise missiles. The Air Force should conduct definitive systems engineering studies to document these assertions, but the cost issue is understood best by imagining each missile disassembled and spread out on a table. Comparison of each subsystem will establish that the overall costs are comparable.

5.4 Long-Range Aircraft

A long-range, multi-use, global attack aircraft (see Figure 30) could be derived from a two-stage, airbreathing RLV. For a vehicle with a staging Mach number of 8 or higher, the first stage could be modified to perform global reconnaissance or strike missions. In situations in which forward presence is denied, or for areas where counterstealth capabilities are deployed, this aircraft could be used for suppression of enemy air defenses (SEAD) or TBM-defeat missions to open corridors for conventional force application. Additionally, a long-range hypersonic strike vehicle could rapidly cover large numbers of targets over large areas in a short period on its own, enabling a parallel war concept of operations (CONOPS) in locations without regional access by friendly forces. Furthermore, hypersonic vehicles enable rapid application of force in multiple locations worldwide, facilitating or enabling multiple major theater war (MTW) operations with short separation times, or even during simultaneous MTWs—a capability not available with today's fleet of aircraft. Through the combination of low-observable features, high speed and altitude, standoff, maneuverability, and self-defense capability, this aircraft could have high survivability.



Figure 30. *A Long-Range, Multi-Use Global Attack Aircraft*

The weapons bay, sized to carry space payloads, could be reconfigured to accommodate a suite of CAVs, each of which could contain a variety of submunitions including low-cost autonomous attack submunitions or small bombs (see Figure 31). These CAVs could also be designed to carry a single penetrating warhead or as a supplement to ISR assets or electromagnetic pulse (EMP) weapons. Additionally, a number of CAVs could carry small unmanned aerial vehicles (UAVs) for battle damage assessment.

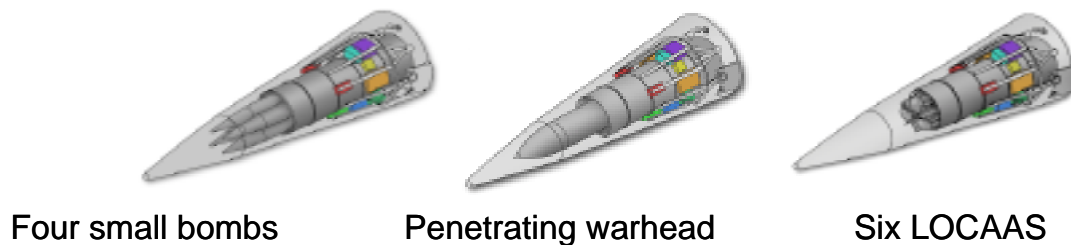


Figure 31. *CAV Payloads*

In addition to the CAVs, the weapons bay of this aircraft could carry an MHD-powered DE weapon. This option is discussed more fully in Section 5.5.

For a two-stage, airbreathing RLV (see Figure 32), having a lower staging Mach number (Mach 4 to 5), both stages could be employed for global attack missions. The first stage could perform the same missions envisioned for the Future Strike Aircraft, and the second stage could be employed in the manner described in the preceding paragraph, assuming that the second stage would be powered by an RBCC engine. It is important to note that design requirements are different for space-access and cruise missions. Therefore, careful attention must be paid in the

early design phase to accommodate them. The feasibility of a dual-use vehicle was shown in NASA design studies conducted between 1995 and 1997.⁶

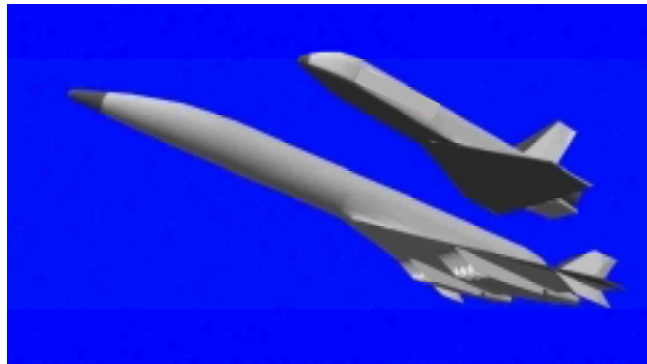


Figure 32. *Alternative Global Attack Aircraft Concept*

Such dual-use vehicles could also be employed to augment conventional transport aircraft. In time-critical, emergency situations, these vehicles could be employed to deliver needed equipment, spare parts, or personnel to a theater of operation in minutes rather than hours.

5.5 Plasma Applications to Aerospace Missions

5.5.1 Power Extraction by MHD

Hypersonic flight offers the opportunity to extract very high levels of electrical power in the range of tens of megawatts from the hypersonic vehicle propulsion exhaust stream. This power source uses well-understood physical principles and engineering. Figure 33 shows a conceptual design for an MHD power-extraction system coupled to a scramjet engine. The power availability increases with flight speed. Energy can be derived by using some of the electrical power to ionize the air in the engine inlet. Chemical seeding of the inlet air may also be used.

⁶ L.F. Scuderi, G.F. Orton, J.L. Hunt, AIAA Paper No. 98-1584, *Mach 10 Cruise/Space Access Vehicle Definition*, April 1998.

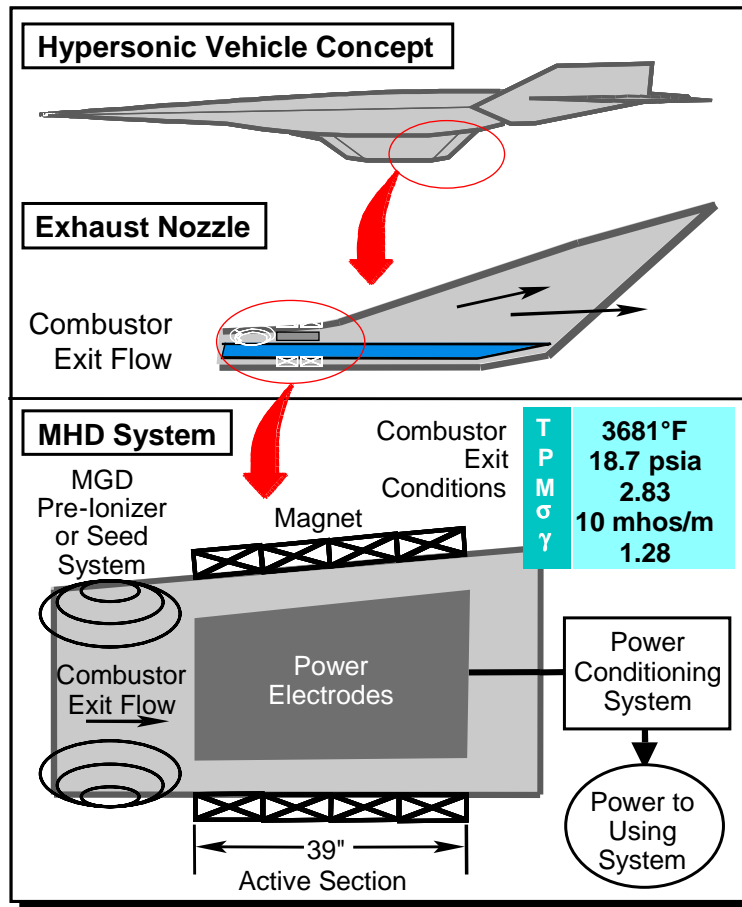


Figure 33. *Conceptual MHD Design*

Based on the specific vehicle configurations, power levels that can be derived appear to be in the megawatt range, or about 0.2 percent of the total available power—without the use of moving machinery. Such power levels are sufficient to drive both offensive and defensive DE weapon systems. Offensive weapons include high-energy laser and microwave directed-energy systems to support the Air Force vision for very high-speed global engagement, whether on land or in space. The estimated weight for the power generation and laser system is about 8,000 pounds for a 1- to 2-MW output laser, based on an industry preliminary design study.

5.5.2 Improved Hypersonic Vehicle Performance

In addition to providing a power source for generating electrical power by MHD, plasma effects around the hypersonic vehicle provide opportunities for further enhancement of vehicle performance. A microwave beam or electron beam can be projected ahead of the bow shock of the vehicle to ionize the incoming gas. The result of the ionization is to reduce the vehicle drag and reduce heating by altering the shock itself. The effect has been demonstrated in small-scale laboratory experiments but the theory is not yet fully developed. Drag reductions of 10 to 15 percent have been demonstrated in laboratory tests. The corresponding reduction in a leading-edge heat load of 50 percent has also been achieved in laboratory tests.

Vehicle maneuverability may also be enhanced through plasma effects. One concept is based on creating plasma in the magnetic field around the vehicle, resulting in changes in airflow and thus vehicle lift. Such maneuvering capability is achieved without the use of control surfaces or thrusters. Another application of magnetic fields is thrust vectoring using the magnetic field from the MHD generator to deflect the ionized exhaust gas. This effect has been demonstrated in the laboratory and simulated using available computer codes.

Finally, the same plasma effects may be used to modify the airflow into the engine inlet to produce inlet flow turning and compression along with improved shock control. This capability has been demonstrated in the laboratory but requires another magnet and its weight penalty.

5.5.3 Findings and Conclusions

The use and modification of hypersonic vehicle (above Mach 10) exhaust plasma to drive directed-energy offensive and defensive weapons is a potentially radical breakthrough in offensive vehicle capabilities. Significant technology risks exist but the operational benefits are worthy of an R&D effort to verify the feasibility.

The technology base for plasma applications by aerospace vehicles is reviewed in Sections 3.3.3.3 and 7.2.3. The US effort is judged to be significantly behind the Russian effort in many critical areas (see Section 4.8).

5.5.4 Operational Opportunities From Power Generation

Counterair capability is provided by the high-energy laser system. The energy level might provide a kill range up to 100 km for aircraft, TBMs, and cruise missiles (see Section 7.2.3.1). CONOPS opportunities for directed energy include the following potential advantages:

- Zero time of flight
- Many soft targets
- Wide-area, long-range coverage
- Surprise factor
- Selective targeting
- Self-defense

Air Force application of this weapon system is seen for

- Space control
- SEAD
- Surface attack
- Counterair missions

The SEAD role includes both laser and microwave weapons. The laser operating at a megawatt power level is capable of pinpoint as well as wide-area power delivery. In the pinpoint mode, the laser has power levels sufficient (by a factor of 2 to 3 for 2-second exposures) to penetrate titanium and steel under hazy atmospheric conditions at a slant range of 140,000 ft.

Microwave devices (see Section 7.2.3.2) can be used for electronic countermeasures, enhancing vehicle survivability and attacks on power grids and power-generation facilities. The first two applications apply at relatively short range. The vehicle size and configuration provide a

microwave aperture (along with the available power level) sufficient to induce temporary or permanent damage to ground-based electrical systems at 100,000 ft.

5.6 Penetrators

5.6.1 Operational Concept

A proposed use for hypersonics is the delivery of hypersonic penetrators for deeply buried targets (DBTs) as described in Section 3.3.3.4. Hypersonic penetrators have a maximum effective delivery speed of about 5,000 ft/sec (at approximately Mach 5) and have the potential to destroy some DBTs. The maximum penetration depth is a function of the mass of the device and the velocity with which the device strikes the ground. Maximum penetration depths for granite are less than 100 ft. While there are many critical targets within the penetration depth capability of hypersonic penetrators, many of the most critical targets are more deeply buried than the penetration depth limit for these devices.

Comparison of the weights of a large gravity bomb and an equivalent hypersonic penetrator indicate that the penetrator can be reduced from 5,000 to 250 lb to get a comparable penetration depth. For the GBU-28, the impact velocity is 1,300 ft/sec. In practice, the velocity scaling is more favorable, and the scaled velocity for the lighter-weight penetrator is only about 3,000 ft/sec. This could be an important advantage for use with hypersonic strike aircraft or UAVs. A booster motor on a hypersonic penetrator could provide precision control on the point and angle of impact of the penetrator. These are important parameters in maximizing the penetration depth of the weapon.

5.6.2 Findings

The operational benefit for these hypersonic penetration weapons for DBTs is not judged to be applicable to the hypersonic vehicle program, given the effective limit of these weapons to around Mach 5. Enhanced effects may be produced at much higher penetration speeds (35,000 to 40,000 ft/sec) where impact angle is not a factor. Details are given in Appendix G.

5.7 Fighters

Although the inherent characteristics of hypersonic flight (high speed and energy) would seem to fit nicely with aircraft fighter operations, the panel could find no significant requirement for a future hypersonic fighter aircraft. No postulated future threat systems mandate a requirement for a hypersonic fighter. All forecast threats could be countered by fighter systems in development or by other more efficient means, particularly missiles. In the latter regard, hypersonics does offer some potential for long-range air-to-air missiles for future combat scenarios requiring a long-range (more than 100-mile) standoff.

One potential development that could affect this requirement is another nation pursuing operations in the transatmospheric region (an altitude of 100,000 ft to 100 miles). Hypersonic speeds are required to operate within that region, and today it is not used for any sustained operations. However, any of the nations pursuing hypersonic technologies (for example, China, Russia, India, France, or Japan) could attempt to operate there for military advantage. In that case, a hypersonic fighter could be required to control and exploit the full aerospace continuum when necessary.

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Chapter 6

Alternative Solutions to the Military Needs

6.1 Introduction

This SAB study was conducted in a unique manner, significantly different from the many studies conducted over the past 50 years. Secretary of the Air Force F. Whitten Peters requested, “Please also form a red team to argue the proposition that hypersonics has no military utility, or at least none given costs and available work-arounds.” Thus a red team panel was established to evaluate independently the need for and implementation options for airbreathing hypersonics.

The red team was formed with members with broad backgrounds in hypersonics, space launch, military operations analysis, space policy, and directed energy. The panel participated in all meetings of the Operations and Investment Program panels, gathering and listening to inputs from across DoD, NASA, and industry. Putting aside any personal views of individual members regarding the issues, the red team approached its job as a group of contrarians, looking for flaws in the logic of those arguing the case for airbreathing hypersonics and postulating alternative solutions. This process culminated in a red team briefing to the entire study team at the start of the summer session. The briefing, presented the viewpoint that airbreathing hypersonics technology is not essential for Air Force missions and roles as currently defined, or as the SAB or the Air Force in its space vision statement has been able to forecast. The red team briefing put forward nonairbreathing hypersonics alternatives for each of the four major mission concepts defined by the Operations Panel: space access, high-speed missile, long-range hypersonic strike aircraft, and directed energy.

Chapter 6 provides descriptions of those alternatives. Each section begins with a brief restatement of the Operations Panel description of the military utility of the concept and then discusses the alternative approaches and concludes with a pro-and-con analysis.

While the red team took the negative view throughout the study, its briefing and study chapter should not be taken as a minority report. We are comfortable with the study and support its overall conclusions that the Air Force may need to pursue an aggressive airbreathing hypersonics investment program. The contingency is based on how the Air Force space vision implementation is decided by the leadership. Some implementations of that vision may not require an airbreathing RLV. A rocket-based RLV may be appropriate. Furthermore, it is not yet established that an RLV is required at all. Some interpretations of the vision could call for an asymmetric approach—one that would not require flexible launch to orbit, large orbit plane changes, or suborbital maneuvering. In that case, continued use of ELVs could well be the best, cost-effective military solution. Thus, the red team put forward and supports the continuation of current hypersonics technology programs (for example, Hyper-X, HyTech, and ARMMD) and the concurrent assembly of a comprehensive view of the status of hypersonics technology based on the conclusion of these programs while the Air Force determines the direction and shape of the implementation approach for its aerospace vision. An aggressive airbreathing hypersonics program should be pursued only if justified by that vision and its implementation.

6.2 Space Access

6.2.1 Introduction

The first representative airbreathing hypersonic system selected by the Operations Panel for analysis is a two- (or three-) stage-to-orbit reusable space launch system with a hypersonic, fly-back airbreathing first (and possibly second) stage.

The purpose of this section is to assess the overall viability of proceeding with such an R&D program in the context of its military utility and affordability, the current launch vehicle RDT&E environment, and other alternative approaches to affordable space launch. Chapter 5 contains a more detailed description of the space launch system itself, and how it might be developed and used.

6.2.2 Military Utility

We envision that a TSTO launch system would lift substantial payload weight to LEO at a cost per pound of an order of magnitude or more lower than current or next-generation ELVs (\$800 to \$100 per pound depending on design and launch frequency). Such a system would be designed to be launched, recovered, and prepped for the next mission using procedures as much like current aircraft operations as possible, thereby providing affordable, reliable, responsive space launch to enable on-demand military space operations. Such a system would not only provide for affordable, reliable military space launch, but would also enable many more space and near-space missions (military, civil, and commercial) that today are made unaffordable by the high cost of access to space. Probably no other single technology offers such great promise of enabling the future of military space operations and civil space activities.

In addition, the technologies and subsystems developed for the reusable first stage of this system concept—particularly the propulsion-related technologies—would be applicable to other systems and missions, such as a military aerospace plane, a long-range missile, or a power generator for a DE weapon. These aspects of a hypersonic reusable TSTO space launch system make it the logical pathfinder application for hypersonics propulsion technology. The low-cost, reliable space access it would provide is critically important to almost every contemplated Air Force future space mission, and its technologies are relevant to many other hypersonics applications. See Section 5.2 for a more detailed discussion of the military utility of space access and operations.

6.2.3 Alternative Solutions to Military Needs for Space Access

Based on the reports from a series of panels and commissions held during the mid-90s, a 1996 Executive Order assigned the Air Force the responsibility for maturing and operating the current generation of ELVs and assigned NASA the lead responsibility for developing RLVs, although each agency was to cooperate with the other as appropriate. This decision has focused the Air Force's attention and budgets on developing the current EELV system and NASA's attention and budgets on developing second-generation SSTO launch concepts (for example, the Shuttle upgrade) and technology development for third-generation RLV concepts. NASA's propulsion technology has focused on the development of the linear aerospike rocket engine for the SSTO concept, although NASA has undertaken the small hypersonic propulsion test-vehicle program called X-43 or Hyper-X. Both the Air Force and NASA are relying on the dual-use aspects of

space launch systems to defray a portion of their costs through commercial use of their systems or derivatives. The nation's only partially reusable launch vehicle, the NASA Space Shuttle, offers costs of about \$10,000 per pound to LEO, depending on the mission, while the Air Force EELV program's initial launch contracts provide for costs of as little as \$4,500 per pound. Figure 34 shows the estimated rough order of magnitude cost per pound to LEO for several current and projected launch vehicles.

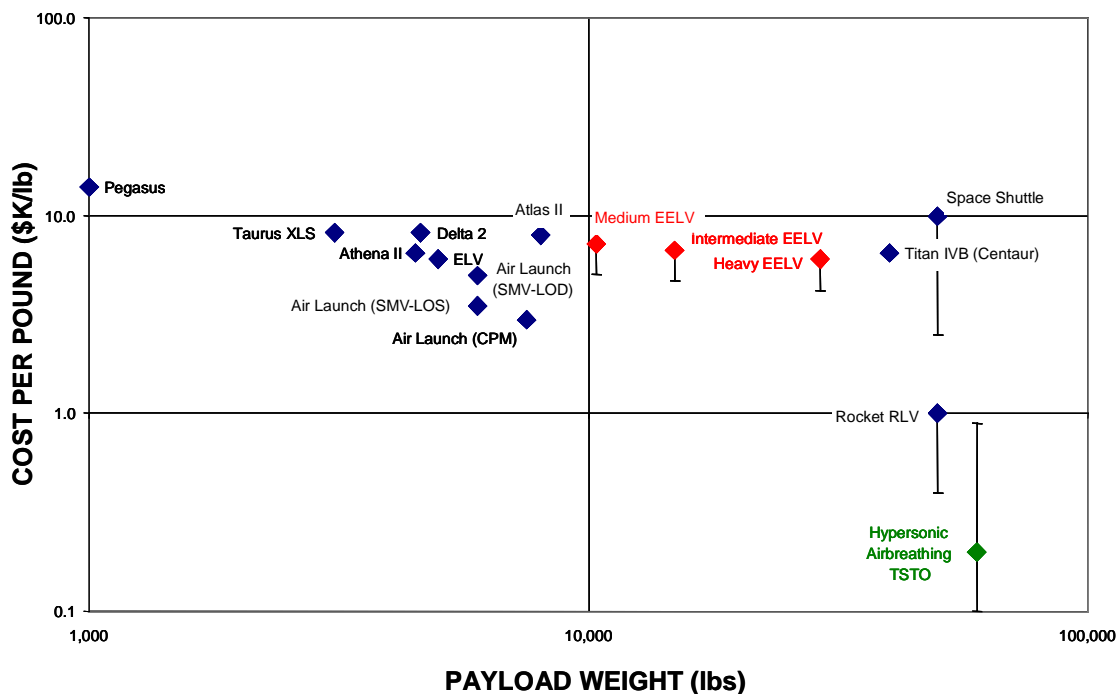


Figure 34. Cost Per Pound to Low Earth Orbit for Several Launch Vehicles

In addition to Air Force and NASA launch vehicle development efforts, a number of commercial and foreign launch vehicle initiatives—such as Boeing's Sea Launch, Lockheed Martin's Proton, the European Ariane, and the Chinese Long March—promise lower-cost access to space as their systems mature. On balance, however, most commercial launch initiatives are less than fully funded and are dealing with launch tempos that are less robust than those of only a few years ago.

6.2.4 Pros and Cons of Various Alternative Space Launch Solutions

Although the red team believes that airbreathing hypersonic TSTO launch systems offer the Air Force the greatest promise of lowest-cost-per-pound, reliable, robust space launch operations leading to routine, aircraft-like military space operations, the development cost of such systems is high. Thus, the red team considered other alternatives available to the Air Force for achieving an improved space launch capability.

The least expensive alternative is to simply maintain the Air Force's planned capability—the EELV program. The Air Force is nearing completion of this development program, which is based on the premise that EELV space launch is a dual-use capability, and that launch vehicle

contractors will take into account the potential commercial and civil launch market when setting their launch prices for Air Force missions. In fact, as Figure 34 shows, the initial operational Air Force contract options for EELV medium, intermediate, and heavy launches (shown in red) offer the Air Force significant cost-per-pound savings over other current systems—as low as \$4,500 per pound under some conditions. These launch costs are well within the affordable range for most current missions, and the EELV is based upon well-established operations concepts for the scheduled launch of cargo or payloads to space. While these costs are an improvement over current systems, however, they still preclude many payloads and military operations missions. Also, EELVs do not have the responsiveness and quick-turnaround capabilities required for military launch operations. For all these reasons, confining our launch capability to EELVs precludes achieving full realization of the Air Force’s aerospace force vision.

Extending EELV technology to produce a more efficient family of EELV vehicles is a viable alternative, but it is unlikely that this technology will produce cost-per-pound improvements lower than about \$2,500 per pound. Nor will it likely produce responsive military operations. Thus, it follows that it is unlikely that the Air Force will ever be able to achieve an aggressive aerospace force vision by relying on ELVs for its access to space.

Another alternative the Air Force could pursue is the development of a lower-cost launch capability—either expendable or reusable—by NASA, the commercial launch industry, or foreign suppliers. This approach would have no impact on the Air Force RDT&E budget, and potential economies of scale would accrue if the Air Force shared the use of others’ infrastructure. The Air Force could even develop a CRAF-like model to ensure access to adequate space launch capabilities if the national security situation demanded it. However, it is unlikely that the commercial vehicles developed will be optimal for Air Force warfighting and space control missions; indeed, control over the development of future Air Force launch capabilities would not reside with the Air Force, but with external entities. It is even possible that, if a foreign entity were to achieve market leadership with a commercial space launch capability, the United States would lose its predominance in space—a situation with potentially serious national security implications.

If DoD, NASA, and commercial launch interests were to engage in the joint development of a reusable hypersonic airbreathing vehicle, the potential for significant development cost savings for each sector would be realized. This alternative probably offers the highest potential for significant launch cost reductions as well, implying that it might better enable the relatively early development of Air Force military transatmospheric and space operations than the other options considered. The potential for other military, as well as civil and commercial spinoffs—and thus significant economies of scale—would most likely be realized with this alternative as well. On the other hand, undertaking such a complex, high-risk development program through a partnership among several organizations with potentially competing requirements would lead to a very complex shared program-management situation—a circumstance that has more often led to shortfalls in program achievements than to success. In particular, the unique Air Force requirement for routine, military, aircraft-like operations driven more by mission requirements than economic considerations may be compromised.

6.2.5 Research and Development Costs

The development of a hypersonic TSTO launch capability would require a massive effort that has been estimated at \$15 billion to \$25 billion over 15 to 20 years after a decision to proceed. It is also generally accepted that the current level of hypersonic space launch R&D—less than \$10 million per year is spent in several agencies—is not sufficient to produce enough technical information to validate current assumptions about development cost, risk, and system capability, or to justify a rational decision to proceed. Even if the operational costs and capabilities were validated, the development costs—estimated at \$1.5 billion to \$2 billion per year—are so large that they cannot be accommodated in the Air Force or NASA budgets without major impact on other important programs. This implies some sort of a cooperative development effort and reliance on the launch programs of several government and commercial entities to amortize the development cost and achieve the economies of scale necessary to yield the desired low-cost-per-pound performance. Another possibility is to make the case that this capability is such a key element of our national power that additional funds either from the budget surplus or from elsewhere in the DoD budget should be provided.

If the Air Force is to use the TSTO space launch system to enable future-generation air and space operations, the systems to conduct those operations must be developed as well. Systems such as the SMV, the CAV, the SOV, advanced weapons concepts, and global C⁴ISR represent major development undertakings in their own right. Thus, the total development cost of moving from current-generation launch systems (which are delivering payloads to LEO for \$4,000 to \$10,000 per pound) to an era of aerospace operations using hypersonic TSTO launch vehicles is likely to be substantially more than the \$1.5 billion to \$2 billion estimated annual development cost for the hypersonic TSTO alone.

6.2.6 Infrastructure and Support Requirements

The infrastructure and support requirements for a hypersonic TSTO launch system would be extensive as well. The system will require extensive spaceport and ground support facilities to support rapid-turnaround aircraft-like operations, including efficient, affordable energetic fuels and materials handling. Questions of fuels and materials handling will drive a major and early system trade—whether to use high- I_{sp} but more-difficult-to-handle hydrogen or less-energetic but easier-to-handle hydrocarbon fuels. In addition, substantial improvement and modernization of our hypersonic RDT&E infrastructure will be required if the Air Force chooses to proceed with hypersonic propulsion systems development of any sort.

6.2.7 The Business Case for Hypersonic Space Access

Simple examination of a hypothetical, rudimentary business case shows that it is very difficult to justify the development of hypersonic space access solely on economic grounds given the current launch demand.

The launch cost for current space systems typically runs about half of the total mission cost or less—that is, launch costs are roughly equal to payload costs for our larger, more complex systems. For example, a recent estimate of the cost to completion of the Space Station is about \$96 billion, of which \$49 billion is launch costs (accrued by the Space Shuttle at about \$10,000 per pound). National Reconnaissance Office (NRO) systems are said to exhibit similar characteristics. If we imagine a space mission cost of 1, then the effects on the total mission cost

of reducing launch costs by factors of 2 to 10 are shown in Figure 35. The figure shows that, as launch costs are reduced from current levels, their impact on overall mission costs is markedly decreased—a somewhat obvious but nevertheless important observation. As we move from current systems delivering about \$10,000 per pound to EELV systems promising \$7,000 down to \$4,000 per pound or lower, the impact of launch costs on total mission costs diminishes so that the economic benefit of developing a hypersonic TSTO delivering even as good as \$100 per pound is relatively small based on current demand. However, reducing the cost of space access substantially may enable the use of different design criteria for payloads as well; for example, it may become cheaper to replace payloads than to build in high-cost redundancy and long mission life.

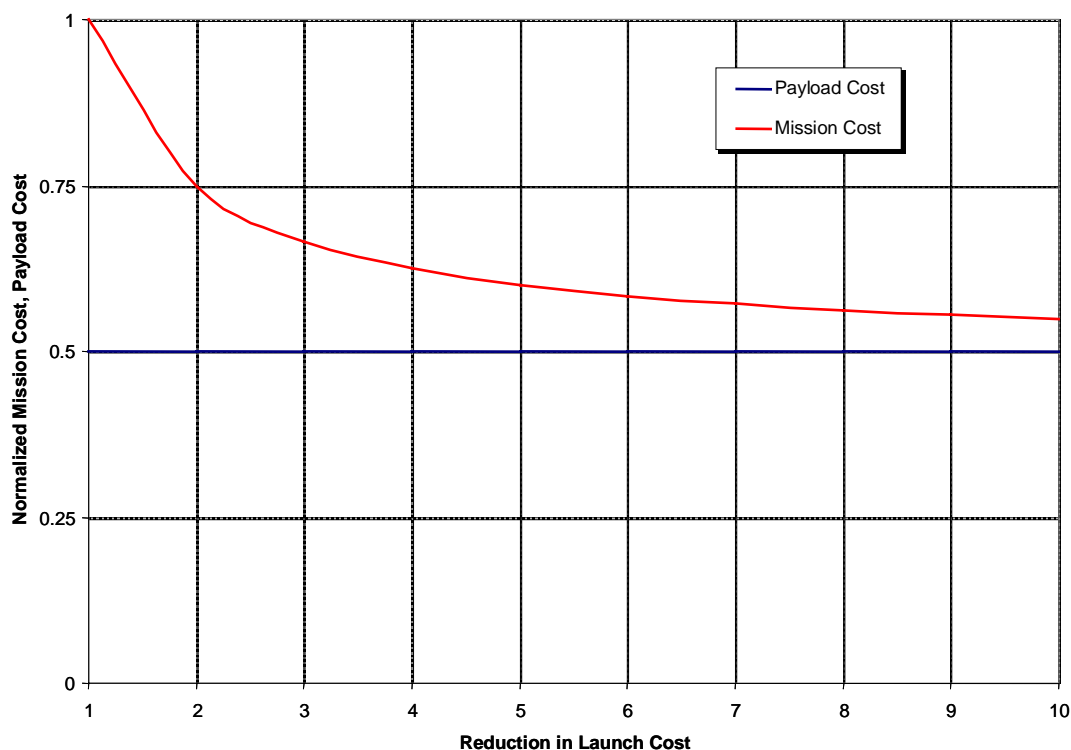


Figure 35. *Effect of Reduction in Launch Cost on Mission Cost*

To illustrate this, we can estimate the time it would take the Air Force to recover its nonrecurring development cost investment in TSTO through savings in TSTO launch costs over the EELV system for several ranges of cost per pound for each system. We assume that, currently, the Air Force sponsors about 20 space launches per year. The average payload weight for each of these launches is about 15,000 lb, implying that the Air Force launches about 300,000 lb to LEO each year. We also assumed a \$25-billion nonrecurring TSTO development program, spread evenly over 15 years for an annual TSTO development cost of \$1.67 billion. We examined an EELV range of \$10,000 to \$3,000 per pound. A cost of \$3,000 per pound is a reasonable estimate achievable by the EELV in the near term. We considered a TSTO range from \$1,000 to \$100 per pound. The results of this simple business case analysis are shown in Figure 36.

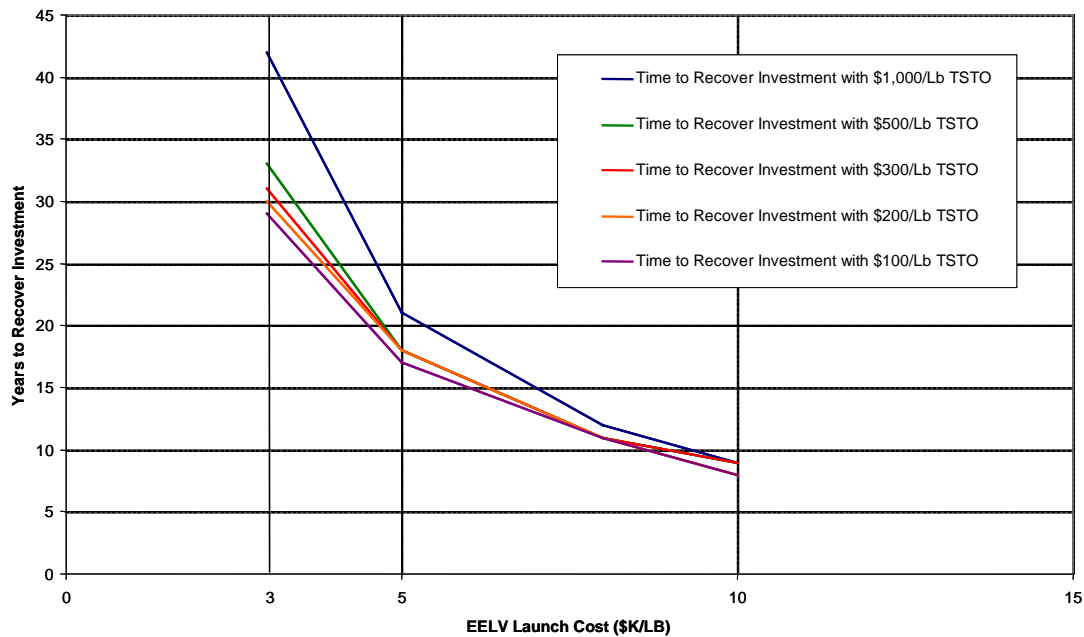


Figure 36. *Time to Recover Non-Recurring Engineering Investment in Hypersonic TSTO From Savings in EELV Launch Costs*

As the figure shows, if EELV costs remain in the region of \$10,000 per pound, then a TSTO of \$1,000 per pound or better makes sense since the time to recover the \$25-billion investment is 10 years or less—a reasonable recovery period. However, if EELV achieves costs of \$5,000 per pound or less, then TSTO must do about \$600 per pound or better to recover its costs in less than 20 years—marginal recovery at best. And if EELV achieves less than \$3,000 per pound, then the TSTO investment will not be recovered for more than 25 years, even if TSTO launch costs are driven to zero. Any net present value or cost of money assumptions would make the recovery period even longer.

This analysis establishes that the economic value of TSTO for a routine space launch is very sensitive to the performance of the EELV. Ensuring that EELV costs are in fact driven as low as possible affects the cost of space access much more favorably than spending a large amount on development to achieve the even-lower launch costs associated with hypersonic TSTO, assuming current launch demand. This is consistent with the rule of thumb that it is almost always economically more advantageous to invest in incremental improvements in current systems than it is to leap to the next generation of new technology, even if that technology promises much better performance capabilities.

6.3 Missiles

6.3.1 Introduction

The development of airbreathing hypersonic weapons (missiles) has been proposed to augment a number of Air Force missions. This section seeks to assess the utility of the missile concept and to propose alternative solutions to military requirements.

6.3.2 Military Utility

Hypersonic airbreathing missile concept seeks to provide weapons in the Mach 6 to 12 range with the mass and form factor of a cruise missile. Such missiles would fit on either fighters or bombers.

Though any surface facility could be made the target of a hypersonic missile, unique targets for such missiles are fleeting targets, such as TBMs, or mobile C² facilities.

A typical timeline for a TBM might entail firing a ballistic missile 8 minutes after coming to a stop. If we assume it takes 4 minutes to search, identify, decide to shoot, and prepare the hypersonic missile for launch, then the hypersonic missile would have to get to the target in 4 minutes. This would allow standoff ranges of 500 km (Mach 6) to 1,000 km (Mach 12).

Attacking enemy SAM batteries might require the ability to out-shoot a SAM in a duel. That would require a speed greater than Mach 6 and a range of about 250 km.

An additional benefit of such a missile is that the kinetic energy available at such speeds might facilitate earth penetrator weapons capable of attacking DBTs. See Section 5.6 for a more detailed discussion on the military utility of hypersonic missiles.

6.3.3 Concept Limitations

Hypersonic missiles have a number of limitations, however. The timelines identified above are inconsistent with current and near-term ISR capabilities. A capability to detect, identify, and engage targets on the move would be of great use no matter what kind of weapon is in question.

The loadout of such missiles is similar to current weapons loads on our combat aircraft, but each weapon would deliver less ordnance; payloads might be only 5 to 10 percent of the weapon mass.

Such small warheads will probably require the incorporation of a seeker and the capability to withstand the rigors of low-altitude hypersonic flight. Neither of these capabilities exists.

6.3.4 Alternative Solutions to Military Needs

Four alternatives to an airbreathing hypersonic missile have been identified:

- Hypersonic rocket
- DE weapons
- Information warfare (IW) to deny adversary their C² ability over TBMs, SAMS, etc.
- Shorter-range weapons for closer approach to target

These options are examined in the following sections of the report. In all cases they are compared to the baseline concept, the airbreathing hypersonic missile. The ability to strike DBTs is described in Section 5.6.

The hypersonic rocket can have performance similar to, or greater than, the postulated airbreathing hypersonic missiles. It can fly on a ballistic trajectory out of the atmosphere and, by discarding spent stages, can achieve similar ranges to an airbreather, while arriving in less time. Examples of such performance are illustrated in Figure 26 of Section 5.3.1.

DE weapons with their speed-of-light effects and the hope of limiting collateral damage seem at first a suitable alternative. However, ground-based targets are extremely hard and are easily made harder. Furthermore, clouds, battlefield smoke, and countermeasures would seriously reduce the operational utility of such weapons. The potential of blinding combatants or civilians might impede their operational deployment. Further discussion of directed energy as an alternative to a hypersonic missile is included in Section 6.5.

The use of IW to deny the enemy their C² capability has appeal because of the low cost and operational flexibility it provides. However, the effects of IW are extremely uncertain, it depends heavily on intelligence.

One way to improve the timeline is to operate at closer ranges, using relatively short-range missiles. For example, the hypersonic missile identified earlier could be replaced by an aircraft operating at 250 km with a Mach 3 missile. The short timelines required are achieved by operating from a closer range. With half the range, two to four times as many aircraft will be required, depending on the particular scenario, and may not be possible at all depending on the threat environment. This may offer a relatively lower-cost solution, fitting well with current CONOPS. Furthermore, this option preserves the targeting flexibility so useful with air assets. The risk to the aircrews could be mitigated by the use of UAVs to the combat arsenals but not without a major investment in a new development and production program with still unanswered technical challenges of its own. Additionally, the logistics footprint and range limitations of UAVs make their operation highly likely in an enemy anti-access environment.

6.3.5 Pros and Cons of Alternative Missile Systems

The red team recognizes the benefits that the speed of weapons provides. However, a number of other considerations affect the decision to deploy a weapon system. The most important issues are discussed below.

The high-speed concepts provide greater standoff than is often available to air-launched weapons; it is useful to explore what might be a reasonable distance requirement for a weapon system. If a weapon is launched from an aircraft, generally the aircraft has an option of flying closer to the target. There are some breakpoints, however. The high-altitude horizon to a target is about 500 km (at low altitude, 50 km). At a range beyond 600 km, treaty limitations may enter, and between 500 and 1,000 km, surface (or sea) basing generally becomes feasible. Thus, the very long range of hypersonic missiles may be in excess of prudent requirements.

The airbreathing hypersonic concepts provide high speed out to even longer ranges. A range of about 600 km provides most of the benefits described above—that is, launching beyond the range (the horizon) of enemy SAMs. If the range is restricted to 600 to 1,000 km, a hypersonic rocket is competitive with airbreathing options. The hypersonic rocket uses technology that is well developed.

The other alternative is to penetrate enemy air defenses and employ shorter-range weapons. This of course depends on a number of factors: signature, countermeasures, tactics, and training by the offense, as well as technology, counter-countermeasures, tactics, and training by the defense. The breakpoints might be 500 km, beyond SAM range (horizon); 100 km, beyond low-altitude horizon; and 50 km, beyond the range of small optically guided SAMs. To achieve the timeline

given by the airbreathing hypersonic missile, conventional air-to-ground missiles would suffice. Speeds of Mach 6, 1.2, and 0.6 would achieve the above ranges in 4 minutes respectively.

Therefore, the choices are (1) to stand off with a yet-to-be-developed rocket-powered missile or (2) if penetration of enemy air defenses is possible, to use current or improved air-to-ground weapons.

The other options considered—directed energy and IW—do not seem competitive at this time and are not discussed further.

6.3.6 Summary

Hypersonic airbreathing missiles allow large standoff ranges against fleeting targets. This capability may be denied to our forces by changes in adversary operations if they can penetrate our ISR and decision cycle. More conventional solutions, such as hypersonic rockets, or attacking fleeting targets from shorter ranges with more conventional supersonic missiles, are available as alternatives. In all cases, fleeting targets will challenge the ISR timelines.

6.4 Long-Range Aircraft

6.4.1 Introduction

For discussion, we assume that an RLV has been developed for other purposes. The vehicle under consideration is an airbreathing platform that flies at Mach 10 with a range of 8,500 to 10,000 nm, a payload weight of 10,000 to 12,000 lb, and a gross takeoff weight (GTOW) of 500,000 lb.

The long-range hypersonic aircraft can be thought of in four related configurations. The most obvious is an airplane that can fly long range from CONUS, deliver its weapons in the proximity of the target, and then return to base. The mission could include the delivery of weapons with a standoff range of 500 nm, which could use a conventional missile or hypersonic missile of the type discussed in Section 6.3.

The second configuration could be a platform that is the first stage of a hypersonic space launch vehicle that would boost a number of RV-like weapons to a velocity that would carry them to their targets.

The third configuration has the same type of platform as the second configuration but launches a bus vehicle that proceeds to the target and dispenses its weapons. These weapons might be the hypersonic missile family described in the first configuration.

A fourth configuration has the same type of platform as the second configuration but carries a DE weapon capable of engaging multiple targets in the air, space, sea, and land domains.

6.4.2 Military Utility

The likely missions for the long-range hypersonic strike airplane could include SEAD; attack of time-critical mobile targets; attack of hardened targets; and other high-value targets. Many of these missions fall into the category of prestrike to clear corridors for a main strike force. The pressing utility for a hypersonic aircraft is rapid time to target, the survivability provided by increased speed, some loiter and search capability, and increased weapon penetration and kill

capability provided by increased impact velocity of penetrator weapons if launched hypersonically.

Additionally, a long-range hypersonic strike vehicle could rapidly cover large numbers of targets over large areas in a short period on its own, enabling a parallel war CONOPS in locations without regional access by friendly forces. Furthermore, hypersonic vehicles enable rapid application of force in multiple locations worldwide, facilitating multiple MTW operations with short separation times, or even during simultaneous MTWs—a capability not available with today's fleet of aircraft.

A major factor in platform requirements may accrue from a particular battle area situation—the target range may exceed any reasonable standoff distance from the borders of the enemy territory, or the bordering nations may exclude bases for launching strikes against the targets in the enemy territories. In either case, overflight of hostile space may be necessary.

The attack of a SEAD target places a high premium on finding the target, platform survivability, and a high kill probability. If we assume that the advantage of stealth may erode in a future campaign, the hypersonic airplane may be the platform of choice to attack this class of targets. One requirement may be sufficient platform speed to outmaneuver or outrun a SAM. This could be accomplished against current SAMs, provided the platform speed exceeds Mach 3 for most SA-x missiles and Mach 6 for the SA-10 and other SA-xx missiles.

TCTs may include long- and short-range missile launchers at fixed sites, mobile missiles and transporter-erector-launchers (TELs), and mobile ground assets. Attack of TELs may be beneficial in situations in which the number of TELs is small compared to the number of available missiles.

The goal of attacking hardened targets is sure kill or functional kill. One may also need to identify and locate the target. This class of targets may be time critical because the target must be negated before it can perform its function—such as loading or unloading materials, closing entrances and air vents, or alerting facility defense systems. Hard targets are the most difficult to kill. A hypersonic penetrator may be the only nonnuclear means to negate the target. However, the penetration depth is limited for conventional penetrators, primarily due to a limitation on the maximum penetrator velocity of about 5,000 ft/sec for steel penetrators.

6.4.3 Infrastructure Requirements

A Mach 10 aircraft with lox-H₂ fuel requires major investments in infrastructure. There appears to be a major break in the technology that affects infrastructure requirements. For speeds above Mach 8, the platform needs to operate with hydrogen fuels, either as a liquid (triple-point) or slush. This would require a major investment in facilities to produce, transport, and service these platforms, which do not exist today. A horizontal takeoff hypersonic vehicle may also incur special runway requirements.

6.4.4 Alternative Solutions to Military Needs

Three of the four mission modes for the hypersonic strike airplane discussed above have alternatives that may be as effective at a lower cost. The concept of a delivery to space of a number of weapons that autonomously proceed to the target is now available in the form of an ICBM, an intermediate-range ballistic missile (IRBM), or a short-range ballistic missile. The

delivery time for intercontinental missiles is 20 to 30 minutes; the time is reduced for shorter ranges. The cost of these systems is minimal compared to other delivery systems. An ICBM is essentially a fuel tank, some fuel, and about a cubic meter of electronic guidance. Typically, a single-warhead missile such as Midgetman (30 tons gross) costs \$50 million; a multiple-warhead missile such as MX delivers 10 warheads at a cost of \$5 million each. These are highly accurate missiles and should be compared to a large airplane platform that costs \$100 million to \$1 billion per platform. The operations and maintenance costs for the airplane are large compared to the ballistic missile. However, the political reality of using conventional ICBMs keeps it from being a viable option.

The concept for launching a bus to orbit that then proceeds to the target and releases its weapons also exists today in the form of ICBMs and sea-launched ballistic missiles (SLBMs). Most of the above comments also apply to this mission concept. The major argument against the use of ICBMs and SLBMs for these missions is a policy issue. The launch of a ballistic missile against a target can be construed to be a nuclear-capable missile, and in a strategic environment it must be assumed to be a nuclear missile. It is argued that a hypersonic airplane would not be construed to be nuclear capable and therefore is a more desirable weapon platform for launching a conventional attack.

Another alternative is to consider medium-range ballistic missiles launched from an aircraft platform. This case is constrained to a missile weight that is typically less than 2,500 lb. There may also be a length constraint. We adopt the tactical missile standard of 168 inches long and 20 inches in diameter, which then could be launched from several fighter and bomber platforms. We also consider a longer and heavier version that is 3,500 lb and 250 inches in length, which could be accommodated in the F-15, B-52, and B-2 bomb racks.

The time-constrained mission solution for short ranges and for ranges in excess of 1,000 nm is clearly the rocket and ballistic missile; the rocket provides rapid acceleration for the short ranges and ballistic flight out of the atmosphere for the longer ranges. At intermediate ranges, the trade-off becomes more subtle. The weight constraint on a missile launched from an air platform leads to range limitations because of physical constraints on fuel and structure mass fractions in the missile for a given payload. This is a valid concern for both single- and multiple-stage rockets. In tactical missiles, the state of the art for fuel fractions in the motor section alone is typically 0.75. When amortized over the other missile structure, this value is reduced significantly. This factor then limits the maximum range of the missile.

Several simple missile designs were considered during the study. However, more-detailed comparison studies for airbreathing missiles and rockets indicate that for ranges of 400 to 800 nm, the airbreathing missile may have unique advantages over the rocket-powered missile. Both ballistic and boost-glide trajectories were considered for the rocket. Because both variants must travel through the sensible atmosphere for this particular range, the higher I_{sp} of the airbreather adds range capability over the weight-constrained rocket. The two solutions provide comparable times to target. The boost-glide trajectories provide additional range to the rocket, but the weight constraint limits the range of the rocket to less than 800 nm. Additional range, however, could be achieved with the heavier rockets that could be carried on a larger platform. Thus, the optimum solution is very scenario-dependent for targets at these ranges. Any optimizations and weapons comparisons for this particular target set must include a detailed study of both missions and technologies.

There are multiple potential alternatives to the concept of flying to target, then delivering weapons. All, however, have a longer fly-out time. The B-2 has been used for this type of mission in Kosovo. The weight of the weapon payload that can be delivered by the standard bomb rack in the B-2 is 16 missiles for a total payload of 40,000 lbs versus the 10,000-lb payload envisioned for the hypersonic strike aircraft. A long-standoff weapon (air-to-ground hypersonic missile, ship- and air-launched cruise missiles, conventional air strike) also could address this mission.

6.4.5 Alternatives to Hypersonic Airplanes

Attacks on SEAD targets could be performed with a cruise missile or with a long-standoff air-to-surface missile. The cruise missile has a long loiter time for search, and it has good survivability—that is, low RCS. The only situation that could obviate this mission is a lack of forward basing, due to either political or time constraints. The long-standoff missile could also do this mission. It could be subsonic, supersonic, or hypersonic. Again the requirement for forward basing applies.

The TCT can typically move out of the kill radius of the weapon's warhead in 2 to 4 minutes. Unless the target is under surveillance by sensors, the hypersonic speed of the weapon is of little use, particularly for a large standoff distance. A Mach 8 missile requires at least 6 minutes to fly to the target from a standoff range of 500 nm. A much better solution may be a UAV with a conventional missile.

Hard target kill could be addressed with a long- or short-range ballistic missile. The reentry vehicle could have a rocket kick-stage to increase the impact velocity of the penetrator, much as Orbital Sciences used a Pershing II to drive a large steel penetrator 45 ft through granite. The impact velocity was 4,000 ft/sec. The impactor package could be launched from a B-52, as it was in the Orbital Sciences demonstration, or as a last stage of a ballistic missile.

6.4.6 Pros and Cons of Air Strike Hypersonic Aircraft

The pros and cons of the alternative solutions to the hypersonic strike aircraft are summarized in Table 2. The first entry under “concept” is the hypersonic strike aircraft along with its pros and cons. The alternatives are listed for comparison: an air-launched rocket; a B-2 conventional bomber; the use of ICBMs, SLBMs, and IRBMs; and conventional cruise missiles.

Table 2. *Pros and Cons of Hypersonic Strike Aircraft*

CONCEPT	PRO	CON
Airbreather (base concept)	<ul style="list-style-type: none">• Reusable• Flexible high-speed global reach	<p>New development and infrastructure</p> <ul style="list-style-type: none">• Requires extensive support for operations• High operating cost
Air-launched rockets	<ul style="list-style-type: none">• Ease of operations• Current technology	<ul style="list-style-type: none">• Low warhead mass fraction
B-2 or other conventional bomber	<ul style="list-style-type: none">• Flexibility• Multiple targets• Current technology• Large weapon load	<ul style="list-style-type: none">• Survivability• Long time to target• Requires extensive support for operations• High operating cost
Ballistic missile	<ul style="list-style-type: none">• Current technology• Low operations and maintenance cost	<ul style="list-style-type: none">• Confusion with nuclear weapons• High cost
Conventional cruise missile	<ul style="list-style-type: none">• Current technology	<ul style="list-style-type: none">• Long time to target

6.5 Plasma Applications for Power Generation

6.5.1 Military Utility

The concept for directed energy being considered within this study is depicted in Figure 37. Missions for the DE weapon include kill of

- Satellites (hard kill to 1 to 2 mm; soft kill of sensors possible to global engagement operations [GEO])
- Boosting missiles (such as the ABL)
- Aircraft (on the ground and in the air)
- Miscellaneous ground targets (for example, troop formations, buildings, vehicles, vegetation, fuel depots, and possibly antennas and ship superstructure components)

It should be apparent that photon energy is not a viable concept against hard targets such as buried facilities, bunkers, and military tanks.

Undoubtedly future technological advances will enhance the ability of the Air Force to accomplish ABL-like missions and more. The example at hand involves a solid-state laser (otherwise known as an electric laser or glass laser) powered by an MHD source. Advantages of solid-state lasers are their few moving components, no messy or hazardous chemicals potential for an “infinite” shot magazine, a scaling potential to megawatts of power, and leverage of the communications industry. The panel was briefed on a heat-capacity laser being developed at Lawrence Livermore National Laboratory at the kilowatt power level for the Army. Apparently, little is required for atmospheric compensation, given that the laser would fly well above the sensible atmosphere (that is, above turbulence, scatter, and absorption). However, beam control to get the energy on target and hold it there is still required and is nontrivial.

An entry-level laser has 1 to 2 MW of power. Laser wall-plug efficiencies of 10 to 15 percent could be anticipated for the electric laser. This assumes that all scalable quasi-continuous wave solid-state lasers are run in a diode-pumped mode (we're not expecting an invention or breakthrough). Such power levels are capable of inflicting lethal fluence on a wide variety of targets, especially those with thin metal skins or those that ignite easily.

MHD power generation is well known, but the application to hypersonic vehicles needs more analysis. The power in free-stream hypersonic airflow at an altitude corresponding to 0.01 atm (100,000 ft altitude) is $P = 0.1 \times M^3 \text{ MW/m}^2$ (that is, per m^2 of cross-sectional area). Assuming an optimistic electrical extraction efficiency of 1 percent at a speed of Mach 10, one could extract electrical power through MHD processes of $1 \text{ MW}_e/\text{m}^2$. If one could duct 10 m^2 of airflow through the MHD power source, 10 MW_e could be available to power an onboard DE weapon. Assuming a 10 percent efficiency for the DE weapon, this could lead to a weapon with an optical beam energy of 1 MW, an entry-level weapon. A similar result obtains for any position in the flow path, such as the engine exhaust.

Several issues need to be addressed to evaluate the feasibility of the MHD power concept. There is a major system trade-off among the size of the MHD duct, the magnet size and weight on the hypersonic vehicle, and vehicle drag (dependent on duct area). The results of this analysis will dictate the optimum size of the duct area and therefore the flow power that is available for electrical generation. If the total available flow area is less than 10 m^2 or the efficiency is much less than 1 percent for the MHD electrical extraction efficiency, then the viability of the hypersonic MHD electrical-generation concept is doubtful, and alternative electrical power sources may be more attractive.

If a sufficient flow area is shown to be available, several plasma issues need to be addressed for the MHD power source. These are summarized in the MHD power-generation analysis in Appendix F. Alternative methods for high-efficiency electrical power generation should also be considered for this application.

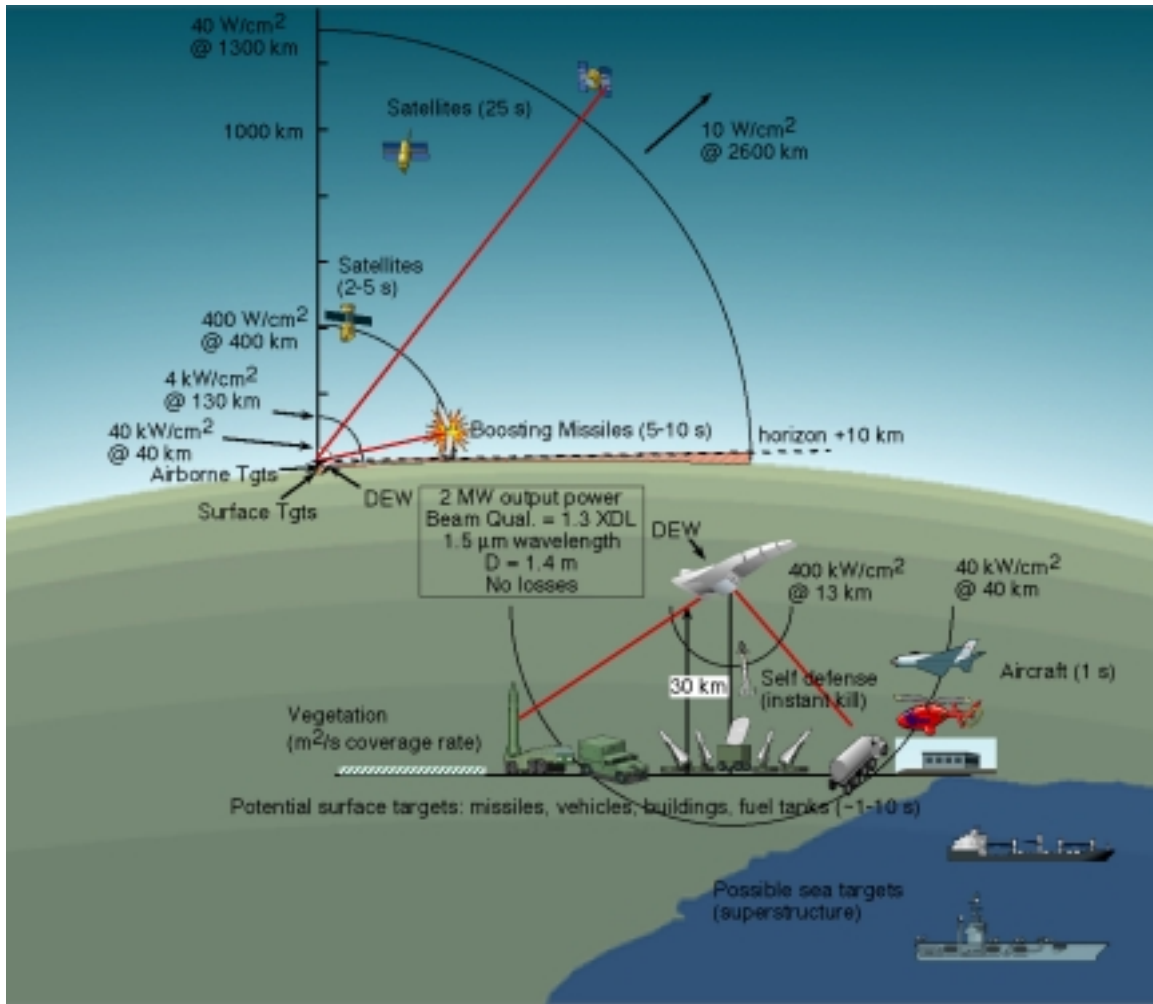


Figure 37. *Depiction of High-Flying DE Weapon (Aboard Hypersonic Aircraft) With Capability Against a Set of Space, Air, and Ground Targets (estimated kill times are in seconds)*

6.5.2 Alternative Solutions to Military Needs

Clearly, fast missiles are alternatives to directed energy, though for many Air Force missions it is difficult to postulate a fast-missile solution to substitute for what are effectively Mach 1 million missiles (that is, photons). Boost-phase kill has proven incredibly difficult for missiles to accomplish, though a Mach 10 to 20 missile could make it practicable. (At 500 km to target, a Mach 10 missile covers the gap in 151 sec, by which time most TBMs would be well beyond burnout. The ABL is assumed to kill the boosting missile while the tank is still pressurized.) For less time-critical targets, missiles are a reasonable alternative to DE weapons, and they are not as limited by weather, which can severely limit DE weapon coverage.

For either DE or kinetic-energy weapons, ISR remains a significant part of the time-to-respond equation. Finding, identifying, and aiming at targets often takes far more time than the actual missile flight—making flight time less relevant. (Boosting missiles provide huge and unique infrared or visible signatures. Thus the directed-energy approach to boost kill has a big advantage over kinetic energy.)

As for the DE weapon itself, solid state is not the only approach and is indeed beyond the current state of the art by several orders of magnitude in power. Alternatively there are chemical lasers operating today in the megawatt power class with long run times. Examples are hydrogen fluoride/deuterium fluoride (HF/DF) lasers (such as MIRACL and ALPHA/SBL) and chemical oxygen–iodine lasers (such as ABL). Chemical lasers have an overall advantage over electric lasers: the heat is automatically removed from the lasing medium, whereas with electric lasers the heat is retained and must somehow be removed before the laser destroys itself (or at minimum, before the heat causes severe aberrations). Chemical lasers also do not require a power supply. Chemical laser wavelengths are comparable to those anticipated from electric lasers (about 1 μm), though the HF/DF approach requires running on an overtone to achieve 1- μm performance, a technique not yet demonstrated at high powers. Beam qualities are likewise comparable, with the chemical oxygen–iodine laser being nearly diffraction limited (HF/DF is currently not as good).

For electric lasers to surpass chemical, three milestones must be achieved:

- Power scaling
- Heat removal at high powers for long run times
- Engineering of compact, reliable systems

Otherwise there should be little incentive to abandon the known workable approach.

Power generation for solid-state lasers, though nontrivial, is a problem already solved. The technology for multimegawatt lox-H₂ turbo alternators is here now. A power supply with a 10-MW output capacity would occupy the space of two large executive-size desks set end to end. For hypersonic vehicles of speeds above Mach 8, lox-H₂ is the prime consumable on the aircraft and which could be used to power a lox-H₂ turbo alternator.

6.5.3 Pros and Cons to Various Solutions

In terms of CONOPS, DE affords the following potential advantages:

- Zero time of flight
- Many soft targets
- Wide-area, long-range coverage
- Surprise factor
- Selective targeting
- Self-defense

The red team agrees that these are significant advantages, as evidenced by the Air Force's funded interest in ABL program objectives. In particular, DE weapons (especially high-power lasers) can selectively deliver lethal fluence to targets such as aircraft and missiles (in flight or on the ground), provided the weapons platform is correctly situated and has a cloud-free line of sight. Obviously, as with any weapon, the laser needs to be within range and have the right orientation to fire.

DE weapons are beginning to come of age in the Air Force. The ABL is now in its pre-EMD phase, anticipating lethal capability against boosting TBMs after 2005. (Other missions are anticipated for ABL but are yet to be quantified.) The ABL system comprises essentially all the

components necessary for an airborne DE weapon, including target acquisition, a high-power laser, a beam control system, pointing and tracking, and aimpoint maintenance. It will be, without peer, the most complex optical system ever flown in the air or in space.

However, even the ABL is not expected to operate with nearly perfect beam control, given that atmospheric turbulence will limit the beam irradiance on target to no better than 20 percent of the optimum case. If ABL could fly much higher (at least hypothetically), the performance would approach 70 to 80 percent. A hypersonic aircraft flying at 30 km should achieve that goal or better and kill boosting missiles.

Unfortunately many targets that one might like to kill with a laser are incredibly hard (bunkers, radar antennas, or military tanks) or hidden under cover of clouds, dirt, or protective coatings. And if targets are vulnerable (for example, fuel tanks), these may be easily protected with additional overlays. Other countermeasures may also be conceived that are effective at a much lower cost than increased laser fluence (achieved by an increase in power or aperture, or a decrease in range to target).

The Red Team Panel also foresees nontechnical disadvantages to the directed-energy approach, not the least of which is that lasers are considered unacceptable means of attacking people either intentionally or inadvertently (whereas missiles, bombs, and bullets are acceptable). We believe that this limitation will not disappear. Thus using a DE weapon against ground targets (for example, aircraft on tarmac) requires great care not to cause collateral damage (for example, the blinding of an airman). Even pointing the beam toward a low-altitude airborne target may result in collateral damage on the ground.

As for the laser and laser system technology, many limitations need consideration. Foremost for lasers is heat removal. Heat is a major byproduct of lasers because that which is not coherent light output is heat. Heat must first be extracted from the lasing medium, then disposed of from the aircraft. This second step translates into drag, irrespective of the type of heat exchanger. If the heat is not disposed of (10 MW for a 1-MW laser), optics can be destroyed along with the laser itself, or run times will be very short. With lox-H₂ aircraft, the internal fuel loop can also be used for cooling the laser.

The heat-capacity laser heats to its limit, then cools off in a mode in which the laser is not being fired. This can severely limit operational utility. Typical on and off times are 10 sec and a few minutes, but it can take longer to cool down. An alternative called a fiber laser may do better at removing heat, in that individual fibers are grouped together to provide the megawatt of gain medium. Continuous wave performance is anticipated. Cooling access is improved but at the expense of added technology to maintain phasing between fibers. Both solid-state laser approaches are incredibly challenging and are in need of breakthroughs to reach continuous-wave megawatt power.

The laser alone does not constitute a DE weapon system but requires beam control, including acquisition, propagation (possible adaptive optics), pointing and tracking, aimpoint selection and maintenance, and damage assessment. The principal advantage of a hypersonic aircraft platform is its high altitude (we assumed approximately 30 km), above atmospheric effects of turbulence, absorption, and scattering. This is great for shooting at satellites and boosting missiles; however, there will be atmospheric effects on the beam propagated to targets in the atmosphere, and these effects will be uncorrectable (due to the aberrations being far field). Significant scattering of

energy out of the beam will occur for targets near the ground and for long atmospheric paths (shallow Earth-grazing angles). This can be quantified, but we suggest that a cone half-angle of 45° to 60° under the aircraft is all that could be engaged, and not even that if there are clouds in the path. Additional concerns have been raised about possible aircraft boundary layer effects such as shocks, which could, if not abated by fundamental aircraft and engine design, destroy beam quality.

The envisioned MHD power-generation concept for the hypersonic vehicle has several pros and cons. The advantages are production of entry-level electrical levels of 10 to 20 MW, electrical power available as an engine byproduct with no expendables, and no rotating machinery. However, there is no comprehensive technical or engineering analysis to project the plasma physics of the MHD device or the engineering design of the combined MHD flow channel, the vehicle drag, and the required multi-Tesla magnetic field. Thus there are large uncertainties in the size and weight of the magnetic structure and the vehicle drag. All of these deficiencies lead to high technical risk for the MHD concept.

An alternative to the hypersonic MHD electrical power source is a lox-H₂ or hydrocarbon-fueled turbo-alternator. This alternative is small and lightweight, and its 10-MW units are essentially state-of-the-art. The drawbacks are few, but the concept does employ rotating machinery and requires an auxiliary fuel source. However, hypersonic vehicles normally carry a large fuel load of lox-H₂ or hydrocarbon fuel, and only a small fraction is needed for the turbo-alternator.

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Chapter 7

Technical Considerations for Achieving Hypersonic Systems

The four principal hypersonic concepts identified by the Operations Panel introduce technical issues, which are addressed in this section. In Section 7.1, the general issues of technical push versus technology pull are discussed. Details of the technical issues on the four operational concepts are presented in Section 7.2. A prioritized listing of the required technologies is presented in Section 7.3, and a description of the technology focus needs is provided in Section 7.4. In Section 7.5, the need for a rigorous systems engineering effort to parallel the technology development is discussed. Finally, issues relating to the ground-test infrastructure needed in the development of a hypersonic system are presented in Section 7.6.

7.1 Requirements Pull Versus Technology Push

The evolution of technology has historically proceeded from a combination of societal and organizational needs (“requirements pull”), fundamental scientific and technical advances (“technology push”), and enlightened, forward-thinking technical and technological leadership. The most far-reaching technological advances (for example, development and widespread integration of the Internet) have had very strong contributions from all three areas. The first two, as they apply to airbreathing hypersonics in general, are discussed in this section. The third arena, forward-thinking technical and technological leadership, is beyond the purview and control of this study.

Responsive, reliable, affordable, and flexible space operations are the most far-reaching military technological requirement that can be significantly affected by hypersonic technologies. Regional powers increasingly rely on space capabilities (for example, satellite communications), and the historic investment by foreign powers in space launch capability (for example, the Ariane, Long March, and Proton rockets) has put the United States at less than parity with commercial launches. The greatly expanded military uses of space, ranging from sensing to the potential for space-based weapons, require strong technological investments by DoD (particularly the Air Force) to be able to move away from the Air Force’s reliance on ELVs. As noted previously, rapid, reliable military space access is not likely to be achieved with the Air Force’s (current) sole emphasis on the EELV program.

RLVs hold the greatest promise for low-cost, responsive space access for the evolution of the US capability of full space operations. NASA’s contributions to RLVs are considerable; the second-generation RLV concept under development and examination is the X-33, the prototype of the VentureStar SSTO rocket-based vehicle. Yet NASA’s primary emphasis is on technology development for commercial space launch (especially as it pertains to reduced cost), with additional applications for Space Station crew return and resupply. While there is a strong need for the military to leverage technologies developed for commercial application, NASA’s second-generation and proposed third-generation RLV development programs cannot meet the military’s space operation needs. The Air Force will need to initiate significant technology development for military-based RLV concepts. Airbreathing or hybrid airbreathing–rocket hypersonic vehicles are key candidates for RLV development.

Still important, yet at a lower priority with respect to critical technology needs that can be met by airbreathing hypersonic advancements, are the “requirements” of long-range, high-speed missiles and associated platforms for high-priority, time-sensitive targets and rapid global strike via high-speed aircraft deployed from CONUS. While many of these requirements may be met with either rocket-based hypersonic vehicles or lower-speed supersonic airbreathing vehicles, technological advances in hypersonic airbreathing vehicles for space vehicles can also provide major contributions to meeting the needs in the other areas of application.

The past and current national investment in hypersonic airbreathing technologies, principally by DoD agencies and NASA, have resulted in basic as well as developmental contributions in a wide variety of areas. These areas of technology push include hypersonic propulsion systems (near term), low-speed operation (less than Mach 4) of both TBCC and RBCC systems (near term), onboard MHD power generation (midterm), and advanced hypersonic plasma aerodynamic and MHD flow control (far term).

7.2 Technical Issues Arising From Operations Concepts

Specific technical issues were considered for the four operational concepts described earlier, and details concerning the technical aspects of each are addressed. The specific technologies required are presented in the sections below together with a discussion of the relevant issues that remain to be resolved.

7.2.1 Space-Access System Options

As a precursor to this SAB activity, AFRL supported a study to provide detailed technical data on a range of subjects including the propulsion system options for space-access missions.⁷ The principal issues addressed were rocket versus selected airbreathing cycles, cryogenic versus storable propellants, and single- versus two-stage launch concepts, including the attributes of various staging velocities. Results of this study are summarized herein. To perform this study, it was necessary to introduce modeling that provided the opportunity to vary key input parameters, including the structural and propellant mass fractions as a function of vehicle size, the I_{sp} of the respective engine cycles, and the aerodynamic coefficients for lift and drag. For each propulsion concept, reference vehicle weights were selected, based in part on the desire to establish consistency with vehicle concepts and performance data provided by industry and government sources.

The study covered SSTO and TSTO accelerators to various orbits and payload weights, using either cryogenic H_2 (or cryogenic O_2 in rocket and rocket ejector cycles) or storable JP10 (and storable hydrogen peroxide [H_2O_2] in rocket and ejector rocket cycles). For this study, four engine-vehicle classes were examined: (1) a vertically launched rocket; (2) a vertically launched, fixed-geometry, air-augmented rocket (AAR); (3) a horizontal-takeoff, high-performance RBCC engine; and (4) a horizontal-takeoff TBCC engine. All of the airbreathing vehicles use dual-mode ram-scamjet propulsion at flight speeds above Mach 4. Schematic illustrations of these engine cycles are shown in Figure 38.

⁷ AFRL-PR-WP-TR-2000-2114, *Hypersonic Applications and Technologies for USAF*, July 2000.

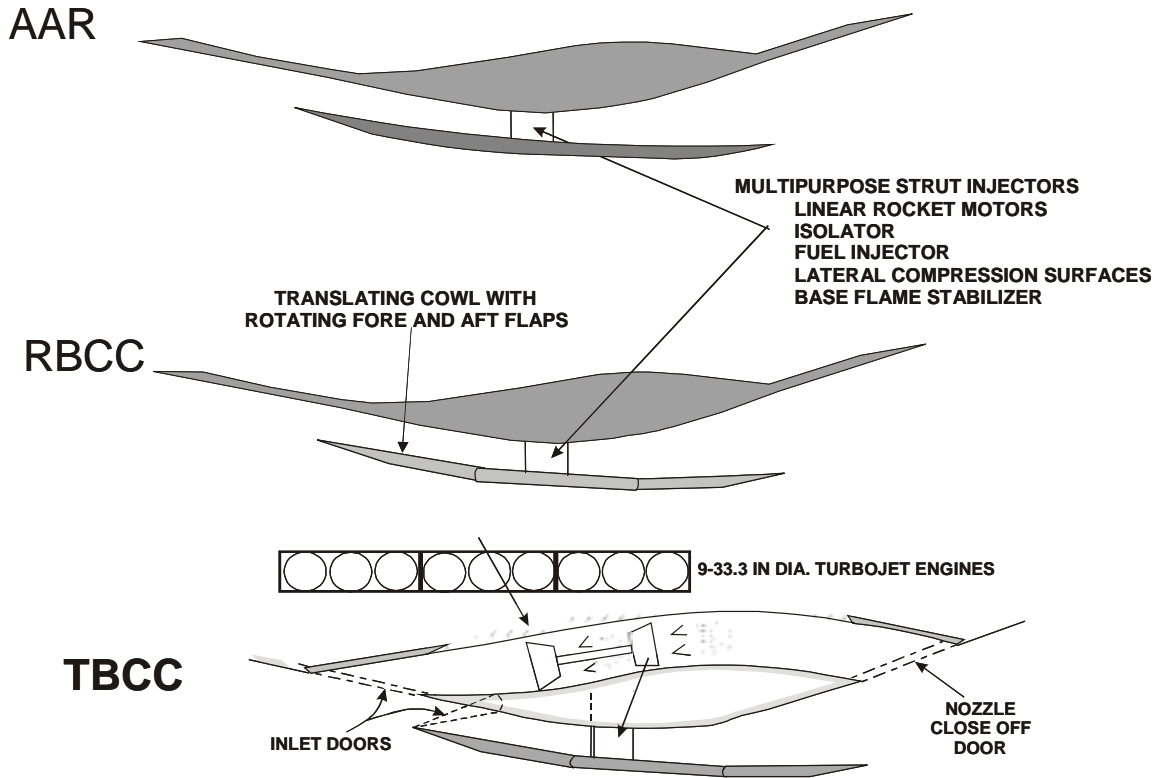


Figure 38. *Schematic Illustrations of Airbreathing Engine Cycles*

The AAR and RBCC classes cover the viable range of design space for embedding rocket engines in the flowpath of dual-mode ram-scamjet engines. The AAR design is based on the use of minimal, if any, variable geometry in the dual-mode ram-scamjet flowpath and thereby benefits from a substantial weight savings. The RBCC requires significant geometric variations in the engine flowpath to realize high engine I_{sp} over a wide Mach number range but is a considerably heavier engine than the AAR. Figure 38 shows that both the fore and aft cowl flaps rotate and the entire cowl translates to provide a variable inlet contraction ratio. The TBCC uses conventional rotating machinery to boost the vehicle to the operating speed of the ram-scamjet. In the configuration shown, the air duct is bifurcated with nine turbojets nested in the body side flowpath. An adjustable flap proportions the flow between the turbojets and dual-mode ram-scamjets during low-speed engine operation. At Mach 4, the fore and aft doors close off the flow to the turbojet duct. Augmenters, typically used in high-acceleration engines, are schematically shown downstream of the turbine.

Numerous design concepts can be modified to the TBCC cycle and yield higher engine performance. A prominent example is the use of heat exchangers to precool the air entering the compressor. The reduced temperature extends the possible operating speed of the rotating machinery and provides a higher engine I_{sp} that leads to fuel savings. However, the weight increases. A cursory analysis of these alternative turbine-based cycles showed that the performance gains, when balanced against weight increases, did not give any significant advantage to accelerator engines. A precooled turbojet could fly to higher speeds than a conventional turbojet. The application that can exploit the attributes of these alternative cycles is

a long-range cruise missile at speeds below Mach 4. There are numerous other cycles not included in this study, some that require heat exchangers to liquefy air, which, for space access, have weights and performance between the TBCC and the RBCC.

7.2.1.1 Cryogenic SSTO Space-Access Vehicles

For each of the baseline vehicles, reference configurations and their respective aerodynamic coefficients were selected from a review of the literature and material provided to the committee in the hearings. Adequate technology levels were assumed to be available around 2010. The first phase of the study was limited to cryogenic hydrogen–oxygen propellant systems for SSTO vehicles. GTOWs (W_T) of 3,000,000 lb for the rocket, 1,400,000 lb for the AAR, 1,000,000 lb for the RBCC, and 1,000,000 lb for the TBCC were selected for the reference vehicle calculations. The reference vehicles were required to place a 25,000-lb payload to 220 nm at an inclination of 51.7°, a typical reference requirement for a NASA vehicle capable of reaching the International Space Station. In these studies, three additional payloads of particular importance to the Air Force were examined: 40,000 lb to typify the lift requirements for the SBL, 12,000 lb proposed for the SMV, and 4,000 lb for the SBR.

The scaling models that were used were indexed to two baseline vehicles—the cryogenic-fueled Lockheed VentureStar and the Boeing Mach 7 hydrocarbon-fueled hypersonic cruiser. The weight models were assumed to be universally applicable for SSTO, TSTO, and hypersonic cruisers.

To avoid the expected controversy claiming bias toward airbreathing solutions, very aggressive rocket motor performance and weights were assumed. I_{sp} values for the RBCC were taken from *Low Speed Operation of an Integrated Rocket-Scramjet for a Transatmospheric Accelerator*.⁸ I_{sp} values for the AAR were obtained from additional cycle calculations. I_{sp} values for the TBCC at velocities of less than 4,000 ft/sec were taken from *Design and Development of Single-Stage-to-Orbit Vehicles*.⁹ Figure 39 compares the engine I_{sp} of the rocket with the three cryogenic H_2 - O_2 airbreathing engine cycles. Engine I_{sp} values for the airbreathing cycles are weakly dependent on altitude. To permit direct comparison with the rocket, all the values shown correspond to altitudes along the respective optimum climb trajectories. Curves are shown as a function of velocity, a more fundamental parameter than a Mach number for accelerating vehicles.

⁸ F.S. Billig, “Low Speed Operation of an Integrated Rocket-Scramjet for a Transatmospheric Accelerator,” *Developments in High Speed-Vehicle Propulsion Systems*, AIAA Progress in Astronautics and Aeronautics, Vol. 165, 1996, pp. 51-103.

⁹ F.S. Billig, “Design and Development of Single-Stage-to-Orbit Vehicles,” *Johns Hopkins APL Technical Digest*, Vol. II, Numbers 3 and 4, July-December 1990.

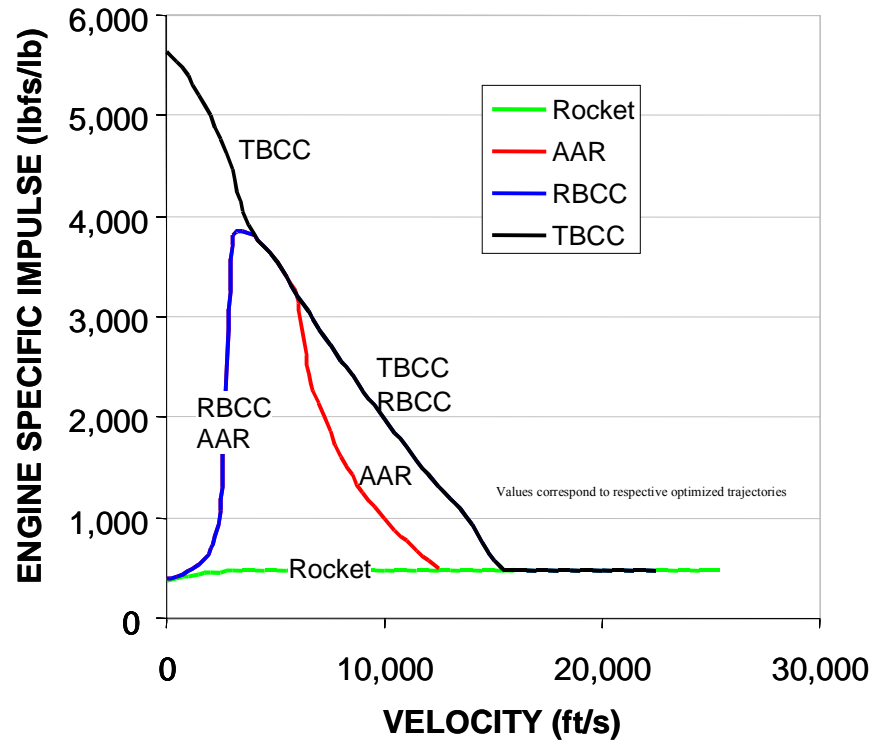


Figure 39. Engine Specific Impulse for Various H_2 - O_2 Engine Cycles

Optimized climb trajectory calculations were made for each of the baseline vehicles. For the access-to-orbit cases, the velocity at the end of the powered climb was 25,400 ft/sec at an altitude of 360,000 ft. The energy level at these conditions meets the transfer orbit requirement to 220 nm at an inclination of 51.7° . The payload for the baseline was 25,000 lb. Trajectories to polar and easterly orbits were also studied, and payload weights of 0 to 50,000 lb were examined parametrically. To account for the different energy levels of the easterly and polar orbits, the changes in the propellant consumption required to yield terminal velocities of 24,206 ft/sec and 25,728 ft/sec, respectively, were determined. These changes were then used to adjust the overall propellant consumption and, in turn, W_T and the vehicle empty weights, W_{EMP} . For the 51.7° orbit, the propellant mass fractions, W_P/W_T , expended to reach the nominal orbital condition are 0.8723 for the rocket, 0.800 for the AAR, 0.740 for the RBCC, and 0.680 for the TBCC.

Ability to vary the vehicle scale is essential to assessing the viability and estimating the cost of competitive design concepts. The approach taken in the modeling of scale effects used herein was to maintain simplicity and flexibility. Simplicity was used to facilitate independent critiques and assessments. Flexibility was used to permit simple parametric changes to be made as new databases become available. Dimensionless coefficients were used to describe the engine performance and aerodynamic characteristics. Establishing procedures for parameterizing weights remains a challenge. For the cryogenic-fueled vehicles, the approach used herein was to adopt the weight of a well-defined recoverable rocket-powered vehicle, the Lockheed Martin VentureStar, as a baseline. A corresponding set of reference vehicles for the three airbreathing systems was also selected. The incremental increases in the structural weight fractions above the baseline rocket were in accord with results from other studies. The models that were introduced

provide a means of estimating the weights as departures from these baseline and reference vehicles for a broad range of vehicle scales. With this modeling, the structural weight W_S as a fraction of the W_T was calculated for each class of hydrogen-fueled vehicles over a range of W_T values. Structural weight, as used herein, comprises the weight of the basic vehicle including the engines. For the baseline rocket and reference airbreathing vehicle configurations at the selected nominal end of flight conditions of 51.7° and 220 nm, W_S/W_T is 0.1144 for the rocket, 0.17714 for the AAR, 0.2300 for the RBCC, and 0.2900 for the TBCC. Note that as the vehicle volume is reduced, the respective “structural” mass fractions increase and the propellant mass fraction decreases. Because the propellant mass fraction is large for space-access vehicles, it was also necessary to model the packaging efficiency of the propellants.

Two arguments that substantiate the veracity of the modeling and the anchoring of W_T for the reference airbreathing vehicles are as follows:

1. When obtained from an existing rocket-powered vehicle design and applied to a scaled version, the deduced effects of scale on weights and performance are in accord with the database
2. When the same model is applied to vehicles using airbreathing propulsion, the thrust-to-weight of the engine $(T/W)_{ENG}$ is consistent with existing or projected engine designs

Also, a fundamental premise is that the weight of the baseline rocket-powered vehicle represents the state of the art and that there is a defined audit trail that realistically relates the weights of all other vehicle concepts back to this one. The baseline VentureStar rocket-powered, SSTO recoverable vehicle has an approximate W_T of 3,000,000 lb. (The exact weight is considered proprietary.) The X-33 is a geometrically scaled prototype about half the length and span of the VentureStar, which will soon be flight-tested. Unrestricted data place the gross weight of the X-33 at approximately 280,000 lb. Eliminating the payload and applying the previously described modeling for a weight scale of 280,000 to 3,000,000 lb yields an empty weight of 68,857 lb with a propellant mass fraction of 0.74409 and a terminal velocity of 15,271 ft/sec. The linear scale factor, based on the model for the ratio of W_T for the X-33 relative to VentureStar, is 0.46. The modeling used herein assumes equitable technology that is independent of scale. However, VentureStar will be using lighter-weight materials and a more efficient propulsion system than the X-33. These combined effects would be expected to increase the empty weight of the X-33 by a few thousand pounds and to decrease the terminal velocity to perhaps 13,500 ft/sec. These estimates, deduced from the modeling, are quite close to those projected for the X-33.

The veracity of the second argument relies on the establishment of the link between the engine weights resulting from the modeling used herein with those that have been generated in other vehicle studies. The basis for comparisons was the incremental weight changes between a rocket and the other engine cycles in vehicles having the same W_T . The deduced value of the $(T/W)_{ENG}$ at liftoff or brake release was the metric. The $(T/W)_{ENG}$ values deduced were 25.71 for the AAR, 18.23 for the RBCC, and 11.667 for the TBCC. These values are in accord with current projections for these engine cycles. The relative weights of other vehicle components (in particular, the respective thermal protection systems) would impact these deduced values of $(T/W)_{ENG}$, but the impact on the major conclusions of this study would be minimal.

Figure 40 shows the results for applying the modeling to examine the sensitivity of GTOW and empty weight as a function of payload for the International Space Station (ISS) orbit for the four

engine cycles. The values of GTOW for easterly orbits are about 20 to 30 percent lower and for polar orbits about 10 percent higher than those for the Space Station orbit. GTOW values for the airbreathing systems are considerably lower than for the rocket system, approximately 0.45 for the AAR and 0.31 for the RBCC and TBCC. Horizontal launch becomes a viable approach for the airbreathing systems, but the GTOW is about twice that of the NASP objective. Empty weight is frequently cited as being more directly related to cost than GTOW. On an empty-weight basis, the differences between the rocket and the airbreathing alternative propulsion systems are considerably smaller but still are significant. Although the GTOW values for the TBCC and RBCC are nearly equal for the same payload and orbital conditions, the empty weights of the TBCC are about 60,000 lb heavier because of the turbomachinery. The empty weights of the AAR are 15,000 to 20,000 lb greater than the TBCC because of the 40 percent larger GTOW of the AAR. Nonetheless, the cost of the AAR would likely be less because of the elimination of most of the variable geometry features of the RBCC and TBCC.

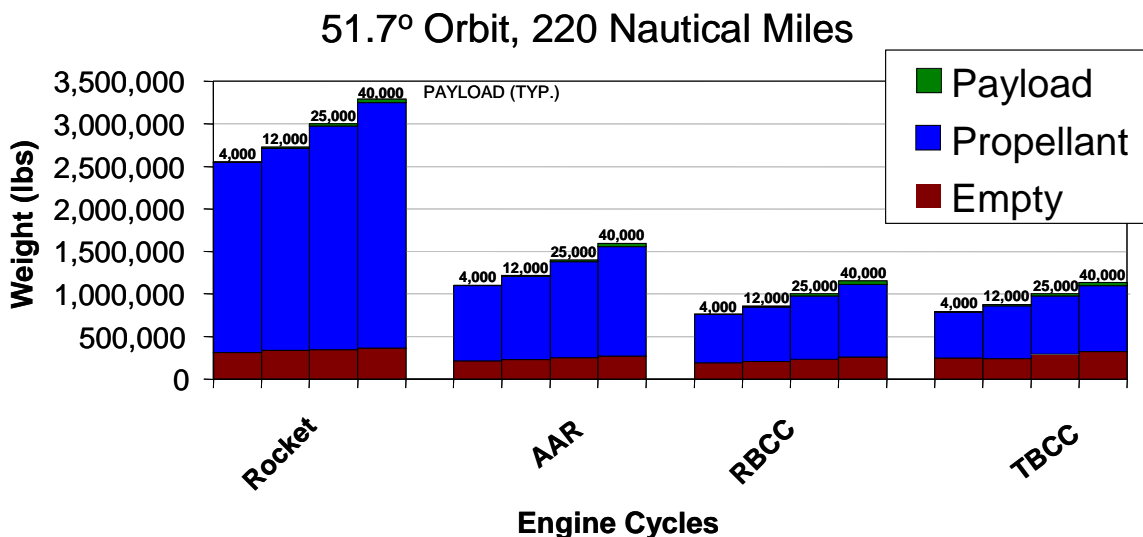


Figure 40. *Weights for Single-Stage-to-Orbit Vehicles With Various Engine Cycles Using H_2 - O_2 Propellants*

In summary, the analysis supports the following conclusions:

- Both rocket and airbreathing-powered SSTO vehicles require structural mass fractions that are very difficult to achieve
- Airbreathing-powered SSTO vehicles offer the potential for a reduction in GTOW to half that of rocket-powered vehicles
- Airbreathing-powered SSTO vehicles offer the potential for lower dry weight compared to rocket-powered vehicles
- Airbreathing-powered SSTO vehicles offer the potential for vehicles weighing less than 1 million lbs, which would help allow airplane-like operations

7.2.1.2 Comparison of Cryogenic SSTO and TSTO Space-Access Vehicles

When applying the described modeling to TSTO systems at selected staging velocities, the payload plus propellant that would have been used to accelerate an SSTO becomes the gross

weight of the second stage, W_{T2} . For the TSTO analysis, the first stages are the four baseline engine cycles, and the second stages are rockets. Just prior to staging, the vehicle would begin to pull up to escape the dense atmosphere that is ideally suited for obtaining maximum performance of the airbreathing engine. Early pull-up would mitigate the thermal loads and thereby lead to lower weights of the thermal barrier system and a more robust vehicle design. Such a strategy is of limited practicality with SSTO vehicles. Early pull-up in an airbreathing SSTO leads to very large increases in GTOW.

Staging velocity was chosen as a fundamental variable in the study. The metric for optimization is the minimum GTOW for a specified payload and orbital requirement. The GTOW was found to be relatively insensitive to staging velocity over a range of 2,000 to 4,000 ft/sec, about the minimum W_T . Figure 41 shows the results for the four classes of engines for a 25,000-lb payload to a 220 nm, 51.7° orbit. Similar results were found for other payloads and orbital requirements. Staging velocity does have a large effect on the respective weights of the two stages and can ultimately impact the choice of the propulsion system and the severity of the thermal environment. Nonetheless, most of the following charts compare results for cases corresponding to the respective staging velocities that yield minimum GTOW. However, the optimal airbreathing vehicle solution would undoubtedly be at a somewhat lower staging velocity. For long-range cruise vehicles, the weight of the propellant that remains following acceleration now becomes available for cruising, or it can be traded for other increased payload or additional passive thermal protection.

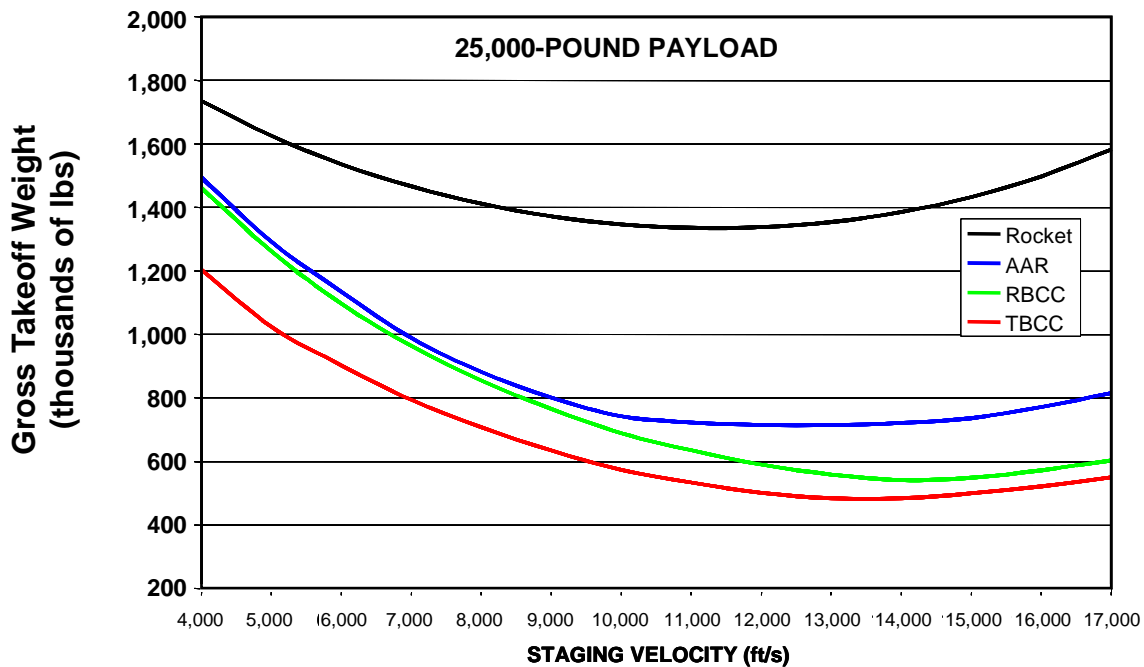


Figure 41. Gross Takeoff Weight versus Staging Velocity for H_2-O_2 TSTO Vehicles to 51.7° Orbit

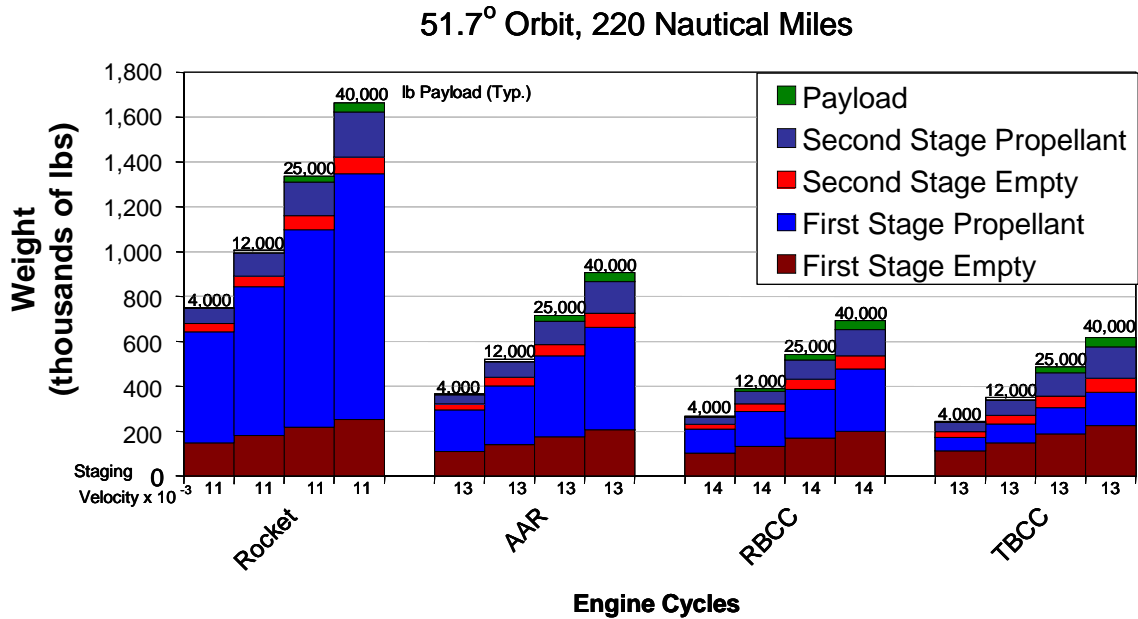


Figure 42. *Weights for Two-Stage-to-Orbit Vehicles With Various Engine Cycles Using H₂-O₂ Propellants*

Figure 42 summarizes the results from the studies of TSTO accelerators using H₂-O₂ propellants in both stages. The propellant, empty, and payload weights for each of the four propulsion systems for the range of payloads of interest in accessing a 220 nm, 51.7° orbit are shown. Similar trends were obtained for easterly and polar orbits. Figure 43 compares the weights of TSTO vehicles with those of SSTO vehicles. These two figures show that the ratio of weights of TSTO to SSTO vehicles vary from about 0.28 with 4,000-lb payloads to 0.5 to 0.6 for 40,000-lb payloads. Reductions in weight lead to lower costs of development and manufacturing and in the ground support infrastructure. Whereas, the weights of the RBCC and TBCC are comparable for SSTO, the TBCC TSTO vehicles are about 10 percent lighter than their RBCC counterparts. The much lower weight of the airbreathing vehicles offers the possibility of mobile basing. Thus transportable, erectable vertical launchers, for example, from a railroad, are a feasible alternative to fixed-land installations.

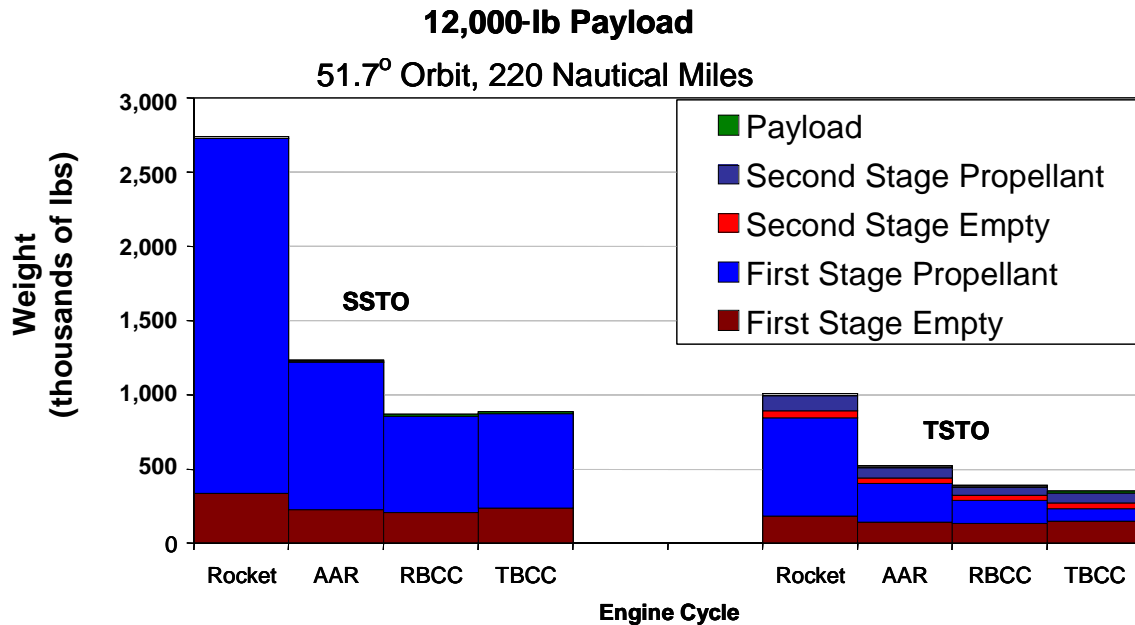


Figure 43. Comparison of Weights for Single- and Two-Stage-to-Orbit Vehicles With Various Engine Cycles Using H_2 - O_2 Propellants

An alternative approach for boosting a 12,000-lb SMV to orbit by either an SSTO or TSTO is to boost the SMV to a lower than orbital velocity and then to use a portion of the second-stage propellant to complete the acceleration. Significant reductions in the GTOW of the system would accrue. For example, if 5,000 ft/sec of the intended 10,500 ft/sec accelerative capability of the planned SMV is used to reach orbit, the GTOW of the system could be reduced by about 60 percent. The extreme sensitivity of GTOW on achievable terminal velocity points out the necessity of meticulously defining the requirements of SMV.

In summary, the analysis supports the following conclusions:

- TSTO vehicle designs require structural fractions that are easier to achieve than SSTO designs
- TSTO vehicle concepts with airbreathing-powered first stages offer the potential for a reduction in GTOW to half that of all rocket systems

7.2.1.3 Hypersonic Systems Based on Storable Propellants

The second part of the study was directed toward examining the performance of noncryogenic propellants for the first or second stages of TSTO accelerators and for hypersonic cruise vehicles. The propellants chosen were JP10 as the fuel and H_2O_2 as the oxidizer. The I_{sp} of the storable propellants is significantly lower than that of the cryogenics; however, the mean propellant density is considerably greater. For the same GTOW, the vehicle is smaller. For the baseline H_2 - O_2 rocket operating at an O/F = 6, the mean propellant density is 23.196 lb/ft³. For the baseline JP10- H_2O_2 rocket operating at an O/F = 6.3, the propellant density is 78.495 lb/ft³, thus the density ratio is $78.495/23.196 = 3.384$. When higher-density propellants are substituted in a horizontal takeoff vehicle, the wing planform area must be increased to handle the higher loading at takeoff rotation. For vertically launched vehicles, the “wing” area is generally sized for landing weights. For vehicles having the same W_T , the empty weights are lower with

higher-density propellants. Consequently, either the wing area remains unchanged and the angle of attack is increased during ascent, or the area is increased to maintain lower angles of attack.

To assess the performance potential of storable propellants, calculations were made to obtain the I_{sp} of rockets, AAR, RBCC, and TBCC-powered vehicles. The cycle calculations were based on 95 percent (by weight) of H_2O_2 with 5 percent H_2O and JP10. This is a strong candidate for a storable system because of its high density and its avoidance of the toxicity problems associated with alternative storable propellants such as hydrazine and nitrogen tetroxide. The stoichiometric O/F of JP10- H_2O_2 is 7.36. Only a few selected flight conditions were examined to determine the ideal O/F ejector motor and ratio of the bypass air to the AAR and RBCC engine cycles. The engine flowpaths were the same as those used for the cryogenically fueled vehicles. A more detailed analysis would be needed to determine optimal engine designs and their respective cycle performances but with this one reservation, the results of the calculations are shown in Figure 44. For the TBCC at all velocities, and the RBCC and AAR at velocities greater than 4,000 ft/sec, engine I_{sp} values are about 37 percent of those shown in Figure 39 for hydrogen. For the rocket, the I_{sp} of JP10- H_2O_2 is about 62 percent of H_2 - O_2 ; the corresponding vacuum I_{sp} s are 294.5 and 475 seconds per pound, respectively. The ratios for the two propellant compositions vary between these limits for the RBCC and AAR for velocities below 4,000 ft/sec.

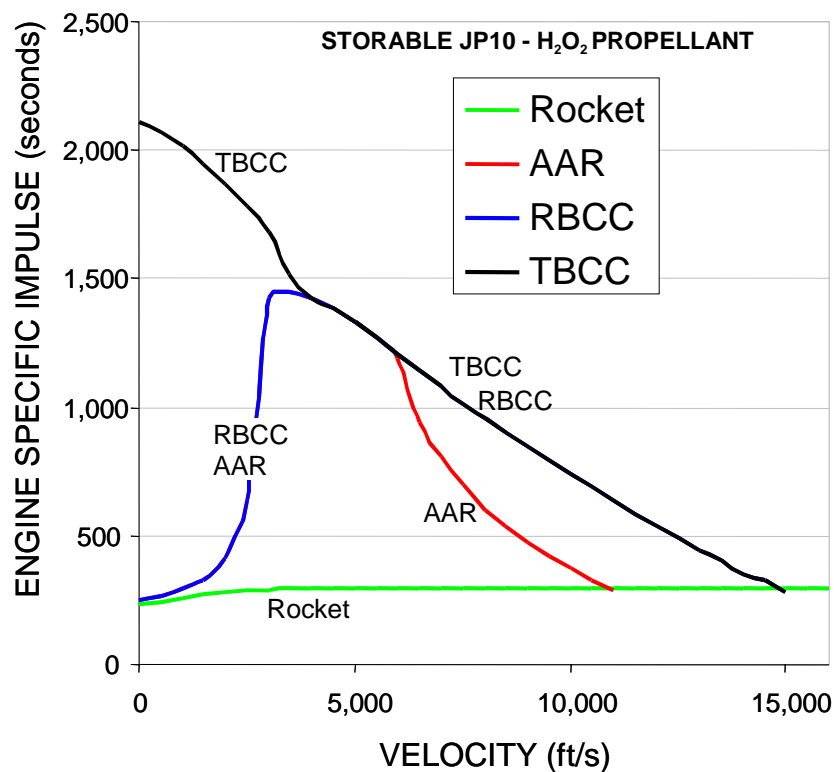


Figure 44. Engine Specific Impulse for Various Engine Cycles

With the I_{sp} defined, preliminary calculations were made to determine the propellant mass fraction consumed as a function of velocity required to access a 220 nm, 51.7° orbit for each of the engine cycles. The mass fractions required to reach this orbital condition are 0.9584 for the

rocket, 0.9298 for the AAR, 0.8794 for the RBCC, and 0.8435 for the TBCC. These mass fractions are so large that the weights of storable-fueled SSTO vehicles would be prohibitively large. Nonetheless, the same data set can be used at lower velocities to evaluate first-stage JP10-H₂O₂ performance for the three airbreathing cycles and for both stages of the rocket.

To enable the use of the modeling developed for the H₂-O₂ propellant systems, it was necessary to establish new reference vehicles. For this study, the conceptual design of a Mach 7 hydrocarbon-fueled hypersonic cruiser developed by the Boeing Company was used as the baseline from which the characteristics of the reference vehicles were deduced. This vehicle has a gross weight of 552,000 lb after in-flight refueling and an empty weight of 167,000 lb. Thus the structural mass fraction is $167,000/552,000 = 0.3025$. The propulsion system for this vehicle is a TBCC. As the first step in defining reference vehicles, the structural mass fractions for the RBCC, AAR, and rocket were determined for comparable $W_T = 552,000$ -lb vehicles. The reverse of the procedure that was used to substantiate the veracity of the reference vehicle weights for the cryogenic vehicles was applied. Accounting for the additional $(T/W)_{ENG} = 11.667$, with $T/W_T = 0.7$ of the TBCC, reduced W_S/W_T for the TBCC from 0.3025 to 0.2425. Increasing $(T/W)_{ENG}$ from 18.23 to 25.71 to account for removing the variable-geometry features plus adjusting the gear weight for vertical instead of horizontal launch decreases W_S/W_T to 0.20756 for the AAR. Reducing the weight further to account for the fixed-geometry AAR engine and the small difference in gear weight lowers W_S/W_T to 0.17949 for the rocket.

The previously discussed modeling can then be used to determine W_S/W_T for a range of W_T values. Comparing these results with those for the cryogenic-fueled vehicles shows that for the same W_T , W_S/W_T values are from 12 to 14 percent lower for the storable-propellant vehicles. As expected, the effects of increased density to reduce W_S/W_T more than compensates for the increase in W_S/W_T because of a smaller scale. Whereas the 552,000-lb vehicles could be used as the reference values, it was decided that a set of space-access vehicles would provide a clearer association to the cryogenic study results. To that end, TSTO systems with a JP10-fueled first stage coupled with a cryogenic-fueled second stage were selected for the reference vehicles. For consistency with the original reference vehicles, payloads of 25,000 lb delivered to a 51.7°, 220 nm orbit were assumed. To obtain the GTOW of the revised reference vehicles, the staging velocity of a H₂-O₂, the second stage was varied until the optimum was found that resulted in minimum W_T . This was a rigorous computation because the payload weight as a function of GTOW is not known a priori. To find solutions, W_T was estimated, W_S/W_T was evaluated, staging velocity was varied, and W_P was calculated. The procedure was repeated until a payload of 25,000 lb at the nominal Space Station orbit with a staging velocity that corresponded to minimum W_T was found. Figure 45 shows $W_{T(1+2)}$ as a function of the staging velocity for the four engine cycles for the JP10 first-stage, H₂ second-stage vehicles. Similar curves are shown for the H₂ first-stage, JP10 second-stage, and for the first- and second-stage JP-fueled engines. The optimum staging velocities are 6,000 ft/sec for the rocket, 8,000 ft/sec for the AAR, 10,000 ft/sec for the RBCC, and 10,000 ft/sec for the TBCC. These are the reference vehicles for JP10-fueled space-access vehicles.

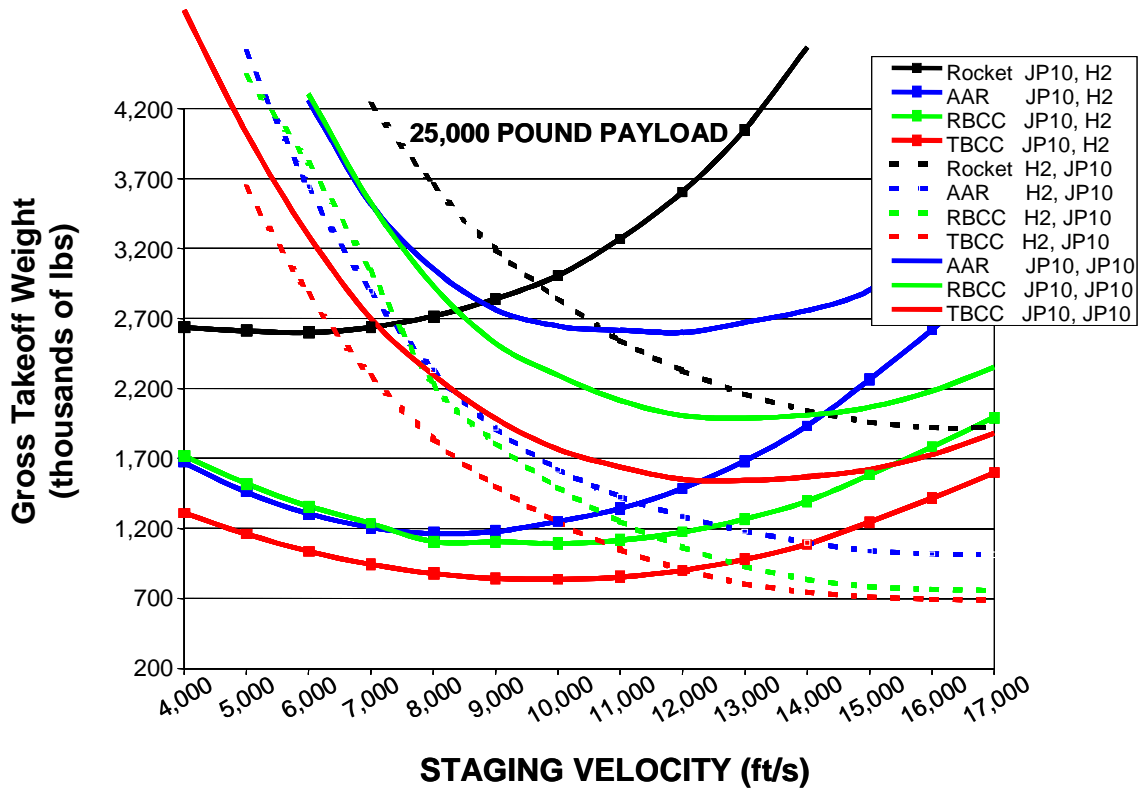


Figure 45. Gross Takeoff Weight versus Staging Velocity for TSTO Vehicles to a 51.7° Orbit

With structural mass fractions, engine I_{sp} s, and propellant mass fractions defined, iterative calculations were performed to determine the weights of vehicles scaled to deliver the four payloads that were described earlier. Calculations were limited to the 51.7°, 220 nm orbit. Figure 46 summarizes the results for the JP10-H₂O₂ first-stage, H₂-O₂ second-stage vehicles. Particular attention should be given to the results for the 12,000-lb payload cases. At present, the most definitive Air Force space mission is the 12,000-lb SMV. Whereas the rocket system is a sizeable 2.11 million lb, the weights of the airbreathing candidates are all below 900,000 lb: 899,000 lb for the AAR, 830,100 lb for the RBCC, and 632,900 lb for the TBCC. Moreover, if the staging velocity for the RBCC and TBCC is reduced to 8,000 ft/sec, the respective GTOW values increase only to 892,400 lb and 679,400 lb, respectively.

51.7° Orbit, 220 Nautical Miles

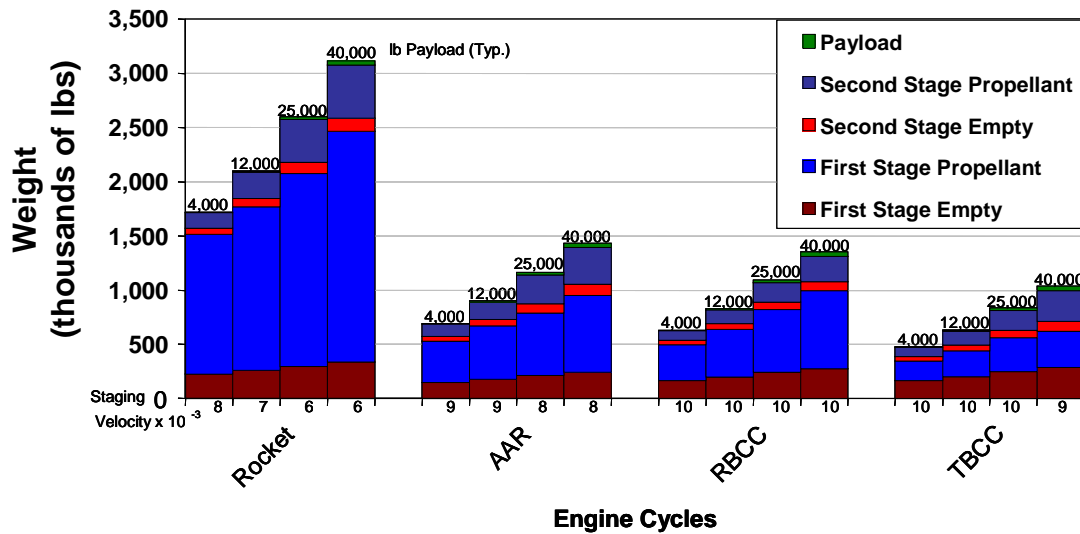


Figure 46. *Weights for Two-Stage-to-Orbit Vehicles With Various Engine Cycles Using JP10-H₂-O₂ First Stage, H₂-O₂ Second Stage*

Specifying 8,000 ft/sec as the terminal velocity of the first stage will enhance the robustness of the airbreathing candidates and minimize development costs, regardless of which candidate engine cycle is ultimately selected. Numerous basic technical factors support this position. They include the following:

1. This is about the highest velocity at which the cooling capability of the propellants can be matched to the thermal load for both accelerator and cruise missions
2. Existing facilities, including affordable upgrades, are available for ground testing
3. The current Air Force HyTech Program is providing a valuable technology base in engine performance, materials, and fuel-cooled structures
4. The cruise velocity of a hypersonic storable-fuel cruise vehicle also optimizes at about 8,000 ft/sec, which provides a dual-use application for the space-access S&T program

These arguments lead to the conclusion that the staging velocity of a storable-fuel TSTO space-access vehicle and the cruise velocity of a long-range strike or reconnaissance air vehicle should be approximately 8,000 ft/sec. When the first stage uses storable fuel and the staging velocity is set at 8,000 ft/sec, there is little difference between the weights, velocities, and cruise vehicle ranges of the AAR- and RBCC-powered vehicles.

Figure 47 compares the weights of the one- and two-stage vehicle capable of lifting the SMV to a 51.7°, 220 nm orbit with various propellant combinations. The most important feature of the figure is the massive rocket that is required for an all-storable TSTO recoverable vehicle. It would weigh about 4.7million pounds. (An SSTO recoverable rocket to provide the same lifting capability would weigh nearly 9 million pounds). Figure 45 showed that the optimal staging velocities for the TSTO all-storable 25,000-lb payloads are 12,000 ft/sec for the rocket, the AAR, and the RBCC, and 13,000 ft/sec for the TBCC. The TSTO TBCC system stage is the lightest of the three airbreathing vehicles. However, relative to the all-cryogenic counterparts, the $W_{T(1+2)}$

values are quite large. Nonetheless, the $W_{T(1+2)}$ values are only 0.37 to 0.57 of the weights of a cryogenic SSTO rocket system. To boost the SMV payload to a 51.7° , 220 nm orbit with an all-storable TBCC TSTO would require a 1.2 million pounds GTOW, which would be heavy for horizontal takeoff. A significant reduction in W_T would accrue if the 12,000-lb SMV would provide a part of the ΔV required to reach orbit. For example, if the SMV would provide 5,000 ft/sec, an easterly orbit could be reached with a $W_T = 549,744$ -lb TSTO TBCC, with separation of a 72,223-lb second stage at 13,000 ft/sec and separation of the SMV at 19,706 ft/sec. A 51.7° , 220 nm orbit would be reached by a $W_{T(1+2)} = 605,020$ -lb, $W_{T2} = 84,889$ -lb vehicle, with the same second-stage separation velocity and separation of the SMV at 20,400 ft/sec. Clearly there is a strong rationale for staging the SMV at velocities below orbital velocities.

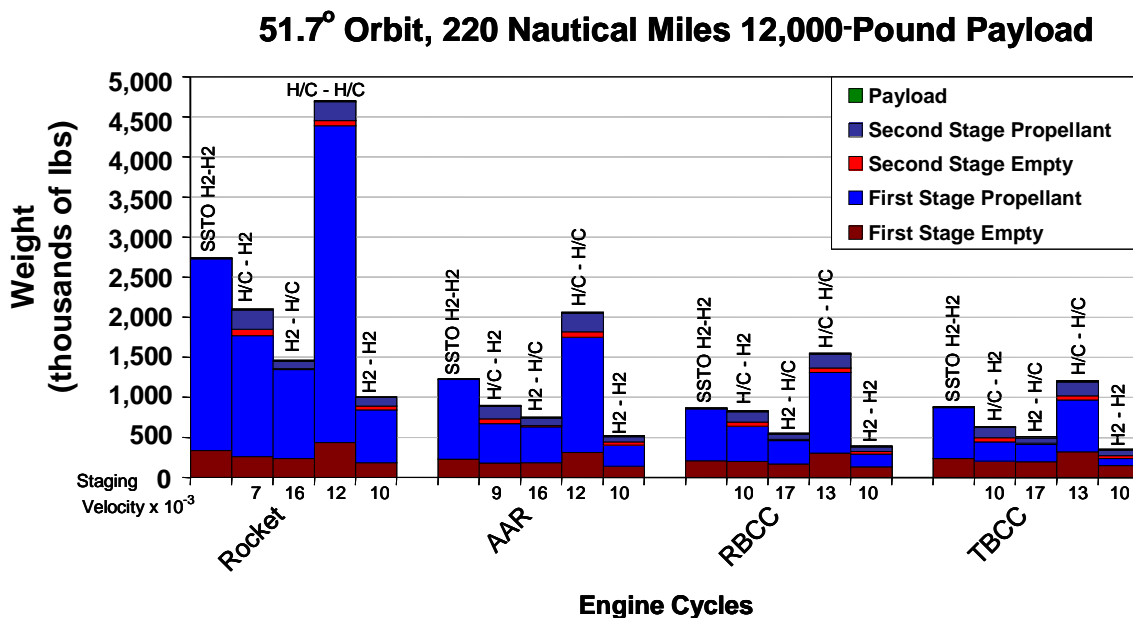


Figure 47. Comparison of Weights for One- and Two-Stage-to-Orbit Vehicles With Various Propellant Combinations

As shown in Figure 45, for the H_2 – O_2 first-stage, $JP10$ – H_2O_2 second-stage vehicles, the optimum staging velocities are 16,000 ft/sec for the rocket and AAR and 17,000 ft/sec for the RBCC and TBCC. These optimal staging velocities remain constant for the range of payloads studied. An interesting result of the study is a comparison of the W_T values when storable propellants in the second-stage rocket replace cryogenic propellants. The growth in GTOW of the vehicles with storable propellants is nearly constant for all engine cycles and payloads. For the entire set of vehicles and payloads, the ratio of the GTOW values varies from about 1.38 to 1.47. The engine I_{sp} is 56 percent higher for the H_2 -based system, but the increased structural weight fraction due to the low propellant density partially compensates. The logistic advantages of a storable second stage could be an important factor in consideration of the use of dense storable propellants. Note that for the SMV payload of 12,000 lb, the $W_{T(1+2)}$ values are 552,895 lb for the RBCC vehicle and 504,727 lb for the TBCC vehicle. Thus with about 60 percent of the weight of an SSTO, a TSTO can lift the same payload with a storable second stage.

The range of gross weights for the airbreathing vehicles shown in Figure 47 varies from 25.6 to 52 percent of the corresponding rocket vehicles. The all-cryogenic-fueled vehicles are the lightest, varying between 37 percent and 45 percent of their respective SSTO counterparts. Substituting storable propellants in the first stage of a TSTO increases the gross weight by 41 to 44 percent and in the second stage by 58 to 77 percent. The all-storable TSTO systems are even heavier than the corresponding cryogenic SSTO vehicles. However, all the airbreathers weigh less than the SSTO cryogenic rocket. Moreover, the all-storable TSTO TBCC is in the weight class of many cryogenic SSTO concepts.

From an operational perspective, a TSTO system where at least one of the stages uses only storable fuels can result in a smaller, more logistically suitable system. Airbreathing propulsion in a combined-cycle engine provides this opportunity. A TSTO system with an airbreathing, storable-fueled first stage having rapid turnaround capability requiring only refueling and inspection could boost multiple cryogenically fueled second-stage vehicles. A TSTO system with both stages using storable propellants would be extremely attractive, but these vehicles tend to be heavy. Conversely, a relatively lightweight TSTO with a cryogenic first stage could serve remotely located bases having an inventory of either storable or cryogenic second stages.

The results of the study have shown that there is no clear choice between the RBCC and the TBCC. The TBCC has distinct advantages whenever the vehicle can benefit from operation at low speed, such as in powered landing, ferrying, and in-flight refueling. Also, there would likely be differences in the vehicle configurations. Nonetheless, there would be considerable commonality in the development program. The RBCC, and particularly the AAR, have simpler, less-costly engine flowpaths and could be developed in less time. Both cycles function as dual-mode ram-scamjets at velocities above 3,000 to 4,000 ft/sec. Both cycles are ideally suited to incorporate modifications to exploit WIGs and MHD power extraction. Consequently, the S&T program should pursue parallel but closely coordinated programs to provide the technology base necessary to develop both TBCC and RBCC/AAR airbreathing engines.

In summary, the analysis supports the following conclusions:

- Airbreathing TSTO vehicle concepts that use storable propellants in the first stage are feasible
- A staging velocity of 8,000 ft/sec for vehicles that use storable propellants in the first stage leads to many desirable features, such as the ability to use currently available facilities

7.2.2 Hypersonic Long-Range Aircraft

A significant degree of overlap exists in the technologies required for an airbreathing-powered space-access vehicle and those required for a long-range hypersonic aircraft. The degree of commonality of these technologies will depend largely on the system architecture selected for the space-access mission and the requirements of the long-range aircraft. Space-access missions that use a TSTO approach could have three possible staging speeds: Mach 3 to 4, for a turbine-based engine in the first stage; Mach 8, for a dual-mode scramjet in the first stage; and a Mach greater than 10, for a hydrogen-fueled combined-cycle engine in the first stage. As discussed in the previous section, staging at Mach 3 to 4 introduces significant weight penalties in the space-access mission. Staging at Mach 8 is near optimum in terms of weight and does not require significant expansion of ground-testing infrastructure. Staging at speeds greater than Mach 10 offers some benefits, especially if the staging speed reaches Mach 20 to 23, at which the first-stage vehicle could be used as a long-range aircraft with global range. In this case, the

first stage could have the capability to fly around the world unrefueled using a skip-glide-skip trajectory. The Mach 4 first stage would have a range capability of 4,000 to 5,000 miles unrefueled. The Mach 10 first stage would have a range capability of 9,000 to 10,000 miles unrefueled. Additional information on long-range aircraft can be found in Section 5.4.

Despite the design and technology similarities between space-access and hypersonic cruise aircraft, there are some significant differences. For example, space-access vehicles are fundamentally accelerators, the trajectory performance of which is driven by the ratio of engine thrust to vehicle drag. Long-range cruise vehicles, on the other hand, are driven by the ratio of aerodynamic lift to drag and tend to be designed as very low-drag vehicles. Hypersonic vehicles, however, are highly integrated, and thrust and drag are not easily separable. This is shown in Figure 48, where vehicle wave drag for a conceptual hypersonic vehicle was parametrically reduced by 25 percent.¹⁰ Because of the highly integrated nature of the vehicle under study, this reduction in wave drag had a pronounced effect on both aerodynamic- and propulsion-related performance metrics. It is these highly integrated flow characteristics that intrigue researchers and designers about the integrated system effects of other flow-related phenomenon, as discussed in Section 3.3.3.3 on plasma applications for aerospace vehicles.

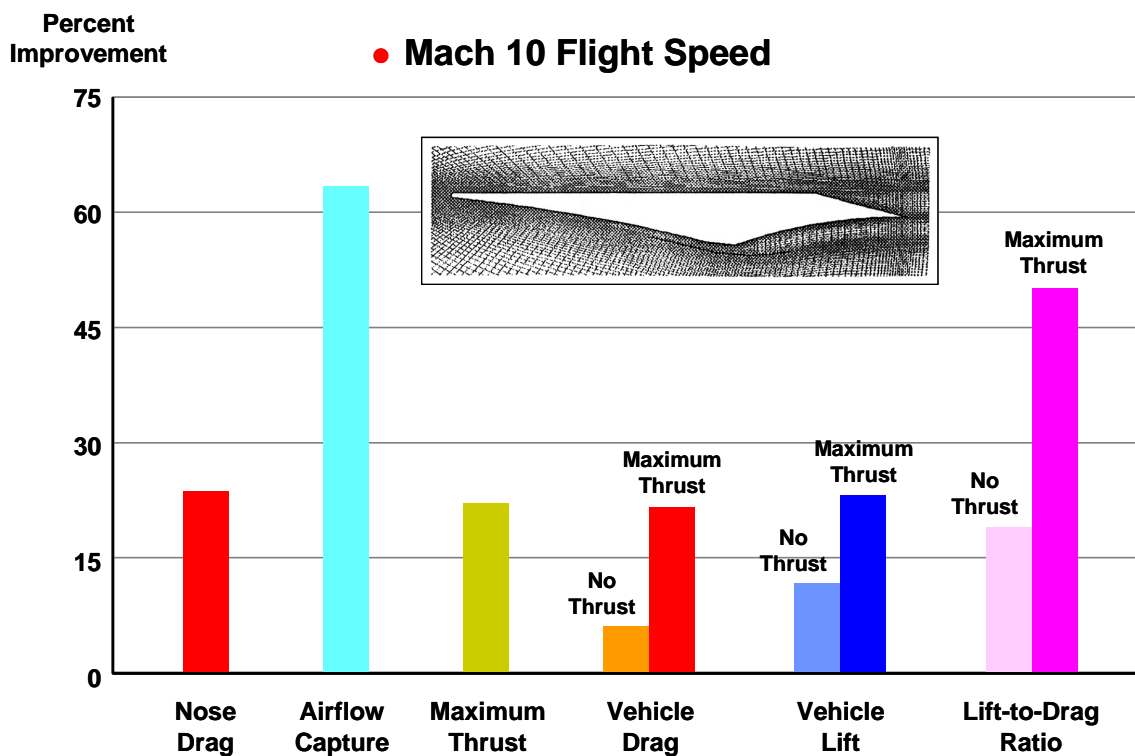


Figure 48. *Impact of Drag Reduction on Aerodynamic Efficiency*

¹⁰ AIAA-99-4975, Comments on an MHD Energy Bypass Engine Powered Spaceliner.

7.2.3 Directed-Energy Weapons

As an outgrowth of space-access and long-range hypersonic aircraft technology, the potential exists to develop a hypersonic DE weapon. When aircraft fly at hypersonic speeds, significant levels of kinetic energy exist in the flowfield. For an airplane of typical size with a free-stream capture area of 30 m^2 flying at a dynamic pressure of 0.5 atm, the kinetic energy per second entering the airplane at Mach 10 and Mach 15 is 4.4 gigawatts and 6.7 gigawatts, respectively. Use of an MHD power-generation system coupled to the propulsion system offers the possibility to access a portion of the kinetic energy for generating onboard electrical power. Ground-based MHD power-generation systems have demonstrated the ability to extract up to 3 percent of the flow energy. For the flight power generation, accessing only 1 percent of the energy would correspond to 44 MW and 67 MW for the Mach 10 and 15 examples.

The principal questions concerning onboard electrical power generation are related to (a) integration of the power generation system within the propulsive flowpath, (b) the magnetic field generation, and (c) generation and sustainment of the flow electrical conductivity.

The energy extraction system can be incorporated into the propulsive flowpath in the inlet, combustor, or nozzle. When incorporated into the inlet, the flow deceleration that occurs as part of the energy extraction can be made part of the inlet compression process. The flow within the inlet is relatively cold, so the sustainment of adequate electrical conductivity presents a particular challenge to this approach. Placement of the energy extraction system in either the combustor or nozzle avoids many of the electrical conductivity problems, since the flow temperature is high and fluid injection (for a potential seed system) is already in place. In all cases, the extraction of flow energy from the propulsive stream results in a degradation of the engine cycle efficiency, although this degradation can be small.

Two options exist for the generation of the magnetic field. The first involves incorporation of permanent magnets. Conventional ceramic ferrites are inexpensive and corrosion resistant, but possess a Curie temperature of 450°C , so if they are used for the permanent magnets, they must be highly cooled. (The Curie temperature is the point at which “permanent” magnets lose their magnetic properties.) Rare earth magnets, such as samarium-cobalt ($\text{Sm}_2\text{Co}_{17}$) with a Curie temperature of 825°C , offer higher temperature capability but require coating to prevent significant oxidation. The second option is to use superconducting electromagnets, which require cooling to liquid helium temperatures but allow for the generation of higher magnetic field strengths.

For the extraction of electrical power using MHD, the flow must be electrically conducting (that is, ionized). The natural ionization within the hypersonic flowfields is insufficient to produce acceptable conductivity, so an artificial means of raising the conductivity must be employed. Seeded and unseeded options exist. In the seeded option, an easily ionized material is injected and mixed into the flow. Typical seed materials are sodium, potassium, and cesium. For energy extraction in the inlet system, the flow is unlikely to be at a sufficient temperature for the seeded system to produce adequate ionization. For extraction systems that are incorporated within or downstream of the combustion process, the seeded system should produce adequate conductivity.

The unseeded systems use some means to increase the number of free electrons within the flowfield. Direct injection of the electrons through the use of an e-beam is the most energetically

efficient means for producing the required level of ionization, although injection of the e-beam into the flowpath presents significant technical challenges. Creation of free electrons through high-frequency or microwave discharges can also lead to sufficient electrical conductivity.

The technology associated with plasma generation and MHD power extraction may also lead to significant improvements in vehicle aerodynamics and propulsion system efficiency. As previously discussed, plasma aerodynamic and MHD flow control offer the potential for drag reduction, lift enhancement, boundary-layer control, and heat-transfer reduction. Despite the immaturity of this technology, there is potential for high payoff in military weapon systems, and this research merits S&T funding until it is better understood.

7.2.3.1 High-Energy Laser

This weapon concept is based on a fiber-amplified phased-array system. A design concept based on MHD power generation is to drive a maximum power level of 10 MW in a single-laser weapon for offensive applications. The power can also be used to drive multiple, smaller-power laser and microwave systems for other operational requirements.

The concept for directed energy being considered within this study is described in Figure 49. Missions for the DE weapon are numerous and include kill of

- Satellites (hard kill to 1 to 2 mm; soft kill of sensors possible to GEO)
- Boosting missiles (such as the ABL)
- Aircraft (on the ground and in the air)
- Miscellaneous ground targets (for example, buildings, vehicles, vegetation, and fuel depots)
- Electronic warfare
- Electrical power generation and distribution system attack

Advantages of solid-state lasers for DE weapon applications are their few moving components, no messy or hazardous chemicals, a scaling potential to megawatts of power, and leverage of the communications industry. The panel was briefed on a heat-capacity laser being developed at Lawrence Livermore National Laboratory at the kilowatt power level for the Army. Apparently little is required for atmospheric compensation, given that the laser would fly well above the sensible atmosphere (that is, above turbulence, scatter, and light absorption). However, beam control to get the energy on target and to hold it there is still required for most targets and is nontrivial.

DE weapons are beginning to come of age in the Air Force. The ABL is now in its pre-EMD phase, anticipating lethal capability against boosting TBMs after 2005. The ABL system comprises essentially all the components necessary for an airborne DE weapon, including target acquisition, a high-power laser, a beam control system, pointing and tracking, and aimpoint maintenance. It will be, without peer, the most complex optical system ever flown in the air or in space.

The laser alone does not constitute a DE weapon system but requires beam control, including acquisition, propagation (possible adaptive optics), pointing and tracking, aimpoint selection and maintenance, and damage assessment. The principal advantage of a hypersonic aircraft platform is its high altitude (approximately 30 km), above atmospheric effects of turbulence, absorption, and scattering. This is great for shooting at satellites and boosting missiles; however, there will

be atmospheric effects on the beam propagated to targets in the atmosphere, and these effects might be uncorrectable (because of the aberrations in the far field). Significant scattering of energy out of the beam will occur for targets near the ground and for long atmospheric paths (shallow Earth-grazing angles).

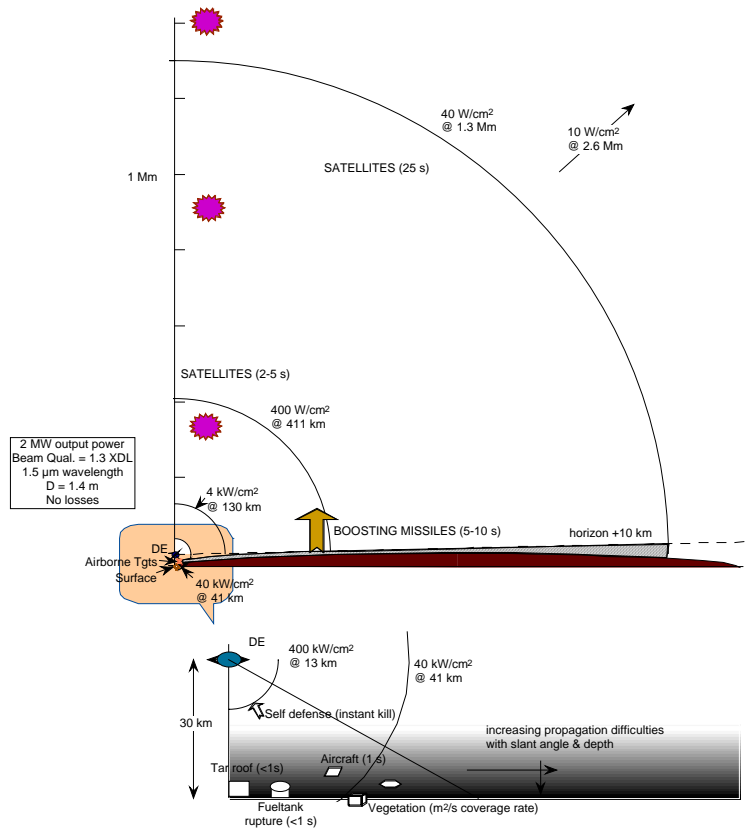


Figure 49. Microwave Weapons

7.2.3.2 High-Power Microwave (HPM) Weapons

Considerable progress has been made in the past several years in the ability to generate and project HPMs. Gigawatt peak powers (average powers of tens of kilowatts) at frequencies from hundreds of megahertz to several gigahertz with a variety of waveforms have been achieved and reproduced. Today such powers are produced from various klystron configurations and projected from classical horn antennas. There is research into solid-state power generation and phased-array antennas, which could make platform integration more practical. Initial tests of effects and propagation have formed the basis for deriving system concepts. A particular challenge is to assess the damage to the target when only electronic upset or damage has occurred. At present, however, useful HPM sources are extremely heavy and bulky.

Foreseeable efficiencies of HPM generators of a few percent means that input powers in megawatts will be required. There will also be considerable power conditioning required, depending on the output waveform used.

HPMs penetrate a target by two primary means: front door and back door. *Front door* refers to entry through existing apertures in the target, such as antennas. *Back door* refers to penetration through coupling to discontinuities in the target structure, such as cracks and holes. There are important ramifications of these multiple-entry modes. First, they greatly complicate the analytical prediction of microwave effects, and second, they are very hard to counter. Therefore, jamming and spoofing of tactical missiles are important applications for HPM. The interaction is primarily with the electronics of the missile and not with the seeker front end (as is usually the case with lasers). It should be reasonable to get effective interaction at ranges of about a kilometer.

Two additional features make HPMs attractive for ground-target attack. First is the ability of HPMs to propagate through most weather conditions. Second is the beam spread, which somewhat relieves target pointing and tracking requirements (but at the expense of higher power to get a given influence on a target).

It is possible to combine the HPM concept with the proven technologies of precision munitions. The notion is to expand the range at which damage to electronic systems occurs beyond the range damaged by the precision munition. The HPM pulse can be produced either explosively or by conventional means. Such a specialized application weapon might be particularly attractive for targets that require careful attack to prevent collateral damage (for example, a hospital next to a command center).

HPM propagation through the plasma around a hypersonic vehicle may cause undesirable effects on the vehicle, the beam, or both. No significant research has been attempted in this area.

7.2.4 Hypersonic Missile Applications

The technology for an airbreathing-powered space-access system can support the development of an affordable hypersonic missile system. Several technical considerations in implementing the missile solutions are recommended in Section 6.2.

7.2.4.1 Rocket Versus Airbreathers

One major consideration is the use of rocket versus airbreathing engines in very high-speed missiles. Long-range rockets will have either single or multiple stages and will require significant improvements over existing systems in propellant loading fractions. Airbreathing hypersonic missiles will likely be two-stage systems with a rocket-boosted first stage and a hydrocarbon-fueled dual-mode scramjet engine to power the second stage. This scramjet engine will have significant technological overlap with that required for a storable propellant airbreathing launch system. Only through rigorous systems engineering studies coupled with near-term NASA and DARPA flight-test data will the optimum missile configuration be selected.

Considerable data exist on the use of rockets in missiles, and the development of a new rocket-based system could proceed with relatively low risk. Most improvements would be evolutionary rather than revolutionary. Usually, rocket engines in missiles are used for quick acceleration, high speed, and short range. On the other hand, data are limited on hypersonic airbreathing engines for missile applications, but the potential exists for extended range, in-flight target redirection, maneuverability for enhancement of survivability, and throttle control for tailoring the trajectory to sensor or submunition requirements.

Technology improvements will allow extended range for both rocket-propelled missiles and high-speed airbreathing missiles. With operation at high speeds and higher altitudes (more than 100,000 ft), the enemy's ability to defend targets will be complicated and could compensate for a potential loss of effectiveness of stealth over time (that is, the enemy could develop more-capable radar systems or use infrared detection and tracking systems or multimode sensor systems).

Rockets and airbreathing missiles also fly significantly different trajectories. Rockets, which fly either ballistic or boost-glide trajectories, operate at very high altitudes compared to the high-altitude cruise trajectory of an airbreathing missile.

7.2.4.2 C⁴ISR Infrastructure to Support a Hypersonic Missile

A second consideration is the current and future C⁴ISR infrastructure capability. According to Air Combat Command, the current C⁴ISR for air-to-ground missions requires hours to days to adequately locate, identify, and target targets. In that type of environment, the speed advantage of hypersonic missiles cannot be effectively utilized, particularly against TCTs. Significant upgrades to C⁴ISR would be required to hit TCTs. These upgrades would include more-capable sensors (possibly including SBR or unmanned combat air vehicle-based sensors), more-integrated communications systems to distribute time-sensitive information (for example, the exact location of a target), and quickened decision-making processes for these time-sensitive targets. Search and identification times of 3 to 4 minutes would likely be necessary to take advantage of hypersonic speeds. Such timelines have already been realized in the SAM environment, although that process is not nearly as complicated as that of air-to-surface. The effects of a hypersonic missile in a greatly improved C⁴ISR environment were tested in wargames (for example, Global Engagement V in June 2000 and futures wargames for the past 2 years), and wargame commanders found the hypersonic weapon to be highly effective.

There is some question about the relative timing of the improved C⁴ISR and hypersonic missile technologies. Should these efforts be sequential or simultaneous? One school of thought says the C⁴ISR issues should be solved before hypersonic approaches are even considered. Another school says that both technologies must be worked together to allow a quicker fielding of a greatly improved Air Force TCT kill capability.

If the C⁴ISR structure cannot precisely locate a TCT, it greatly increases the complexity of the missile system. A seeker and an advanced, high-speed flight control would have to be included in the system, or a means to dispense, at hypersonic speeds, a low-speed seeker system (such as Low-Cost Autonomous Attack Submunition) would need to be refined. Neither approach is easy.

7.2.4.3 Launch Platforms for Hypersonic Missiles

A third consideration is launch platforms. Bombers (the B-52, B-1, and B-2) are the logical choice for a launch platform for a hypersonic missile. The choice of a single platform would set weight restrictions, which would consequently set a range restriction. Modifications to the aircraft could be used to increase the weight restrictions—but that would add cost, especially if a large fleet were chosen. Internal carriage also sets restrictions on the dimensions of the missile and the number of missiles that could be carried. Other platforms, such as fighters, Navy aircraft, and shipboard carriage, could be used. In general these alternatives have lower carriage

capability and hence would provide shorter ranges. Additional platforms, however, might help justify larger production quantities, which would lower production unit costs.

7.2.4.4 Survivability

Through a combination of speed, altitude (greater than 100,000 ft), and low observability, hypersonic missiles provide a very difficult target for intercept, and thus possess a certain level of inherent survivability, but existing advanced systems may already have and future systems are likely to have enough capability that this speed and altitude alone will not guarantee survival. Through a combination of RCS-reduction technology, maneuverability, and tactics, a hypersonic missile is envisioned to present an extremely difficult target for future intercept systems.

7.2.4.5 Range and Cost Considerations

To cover all the scenarios for the release of a weapon from outside the enemy's territorial boundary a 1,500-mile range is needed. The worst-case scenario would be an attack against the Russian landmass.¹¹ A range of 750 miles would be an adequate standoff range for many scenarios, including ones involving Iraq and China. Current and planned long-range missiles have production costs of \$300,000 to \$1 million in large quantities. The DARPA ARRMD goal of \$200,000 in production costs would make it competitive economically with all planned long-range missiles.

7.3 Prioritized Technology Needs

Given the assessments of the required technologies, together with the state of the art, a high-level prioritization of the technologies has been generated.

7.3.1 Hypersonic Propulsion System

Airbreathing space-access vehicles will use either a hydrocarbon or hydrogen-fueled dual-mode scramjet engine for airbreathing engine operation at speeds above approximately Mach 3. The principal technology needs associated with hypersonic dual-mode scramjet propulsion systems are (a) ignition, flame holding, and heat-release control at a Mach greater than 3 but less than 5; (b) highly efficient low-drag fuel injection and mixing schemes at hypersonic speeds; (c) integration of the engine thermal protection system and fuel feed system at a Mach greater than 6; (d) and generation of high-fidelity weight models for the engine and propellant feed systems.

7.3.2 Low-Speed Propulsion Systems

For space-access applications, the selection of the propulsion system for operation at speeds between takeoff and Mach 4 can significantly affect the vehicle operational capabilities. The two principal candidates for the low-speed propulsion system are the TBCC propulsion system, which requires a dual flowpath configuration, and the RBCC propulsion system, which can be integrated into a single propulsion flowpath.

¹¹ *Cruise Missiles: Technology, Strategy, Politics*, ed. Richard K. Betts, Washington, DC: Brookings Institution, 1981, p. 42.

For the TBCC propulsion system, the principal technology questions concern (a) integration of the air inlet system with the requirement for high performance, low distortion, and minimum weight, and (b) integration of the turbine engine exhaust with the main vehicle nozzle.

For the RBCC propulsion system, the principal technology questions concern (a) development of high-performance ejector schemes that maximize pumping efficiency with minimum losses, (b) development of low-cost primary ejector concepts, and (c) investigation of the transition process from RBCC operation to ramjet-scrumjet operation at the lowest possible Mach number.

Several additional propulsive cycles have been proposed for the low-speed system for space-access applications including the PDE, KILN, and ATREX engine concepts. Currently, these propulsion cycles do not justify significant expenditure of resources for space-access applications. In addition, several alternative launch mechanisms, such as MHD or trolley-assist launch, have been proposed to improve vehicle performance. These launch-assist mechanisms are believed to introduce unacceptable operational requirements, so they are not recommended for further investment at this time.

7.3.3 Airframe-Engine Integration

Integration of the propulsion system with the airframe introduces two specific technology needs. The first need is associated with the efficient coupling of the engine operation with the overall vehicle aerodynamics. Proper tailoring of the engine force and moment production, together with the vehicle aerodynamics, are required to take advantage of the high performance potential of the airbreathing engine.

The second technology need concerns the transonic pinch point that exists with most vehicle configurations. Techniques for the accurate prediction of the vehicle net thrust levels and augmentation schemes such as base or external burning should be pursued.

7.3.4 Vehicle Staging, Analysis, Simulation, and Determination

For TSTO vehicles that stage at hypersonic speeds, the separation of the stages must be addressed. For TSTO concepts that employ a rocket-powered upper stage, the separation sequence will likely be preceded by a pull-up maneuver leading to a low-dynamic pressure staging event. For concepts that use an airbreathing-powered upper stage, the staging event may be required to occur at high dynamic pressure. The detailed issues associated with stage separation (including technology limits) must be refined.

7.4 Achieving Hypersonic Technology Focus and Maturity

Given the objective of the development of an operational space launch system and the status of component hypersonic technology, we reached the conclusion that a large-scale prototype vehicle must be built and flight-tested prior to the initiation of an EMD program. This prototype vehicle, an X-Plane, would force the integration and flight demonstration of all the technologies required in a full-scale space launch system. This same programmatic methodology is being used by NASA in the development of a rocket-powered SSTD RLV—the X-33 program. The X-33 vehicle is about one-half the length and one-eighth the weight of the planned full-scale VentureStar.

This recommended X-Plane would be a scaled version of the recommended space launch vehicle. It must have a high degree of traceability to the full-scale vehicle in all of its major technologies, such as propulsion, structures and materials, thermal protection system, vehicle control system, health monitoring systems, and others. It should be used to conduct a rigorous flight-test program, which will provide the required real-world data to enable a reasonably low-risk EMD program. Successful flight-testing of this hypersonic X-Plane would be a key factor in convincing Congress to appropriate the funds for the EMD program. More details of this recommended X-vehicle program are included in Section 9.

7.5 Rigorous System Engineering and System Integration

Although system engineering is not considered a technology, it is a mandatory element of an effective hypersonic S&T program. For the hypersonic development program recommended by this report to be technically and programmatically successful, a sound systems engineering effort must be established and sustained.

7.6 Ground-Based Facilities

Development of hypersonic systems will require a combination of analysis (including CFD), ground-based experiments, and flight experiments. Experiments must be conducted in ground-based facilities to investigate fundamental hypersonic aerodynamic and propulsion issues, component performance and operability limits, dynamic interactions between components, and structural durability questions.

The nation's hypersonic ground-testing capabilities were reviewed by the SAB in 1988 (see SAB Report of the Ad Hoc Committee on Requirements for Hypersonic Test Facilities, May 1989). The state of facilities is such that aerodynamic issues can be investigated over most of the aerospace flight domain, although high Mach number testing must be conducted in short-duration facilities. Propulsion testing on a large scale with run times of seconds to a minute is limited to speeds below Mach 8. Propulsion performance investigations can be conducted at higher speeds using pulse facilities with run times in milliseconds.

There are four primary facility-related issues that must be raised concerning hypersonic system development: (a) the need for structural durability and thermal-balance testing, (b) the need for a facility to conduct RBCC testing, (c) the need for a facility to investigate mode transition in a TBCC engine, and (d) the need for long-duration testing at Mach numbers greater than 8.

The lack of structural durability and thermal-balance testing of propulsion systems is a major weakness of existing facilities where the maximum run time is a minute. Since reusable vehicles uses fuel-cooled engines in which the engine operation depends on the conditions of the injected fuel, sufficient run time must be provided to reach a thermal equilibrium in the engine and fuel delivery system. The United States possesses three large hypersonic airbreathing engine test facilities: (a) the NASA LaRC 8-ft High Temperature Tunnel, (b) the NASA Glenn Research Center Hypersonic Test Facility, and (c) the Air Force Arnold Engineering Development Center (AEDC) Aerodynamic Propulsion Test Unit. Each of these facilities offers advantages and disadvantages for hypersonic engine testing. One facility will require an upgrade to support the required structural durability and thermal-balance testing.

RBCC engine testing in a ground-based facility requires attributes of both airbreathing and rocket test facilities. At present, most rocket test facilities do not support airbreathing test requirements, and airbreathing facilities do not support rocket test requirements, especially for large-scale engine testing. If system design studies indicate that the preferred space-access vehicle is based on RBCC engines, a large-scale facility for RBCC engine testing will be required. Significant infrastructure for this facility is in place at Edwards Air Force Base, and NASA plans to construct such a facility at John C. Stennis Space Center.

A space-access approach that uses a TBCC engine will require a ground-based facility that allows investigation of the mode transition between turbine-based and ramjet-scamjet operation. Since this transition occurs at speeds between Mach 3 and 4, this facility will need to be large to support full-scale engine testing and to operate at supersonic speeds. At present, the Air Force Aeropropulsion Systems Test Facility at AEDC, which is limited to Mach 3.5 speeds, and the NASA LaRC 8-ft High Temperature Tunnel, which can operate at Mach 4 and 5, are the preferred facilities for this testing.

The final facility-related issue concerns the need for long-duration propulsion testing at speeds greater than Mach 8. This type of testing will be needed if space-access vehicles requiring airbreathing operation at speeds above Mach 8 are pursued, and envelope expansion is deemed to present unacceptable risk. During the NASP program, a long-duration direct-connect scramjet combustor facility was constructed for testing at speeds up to Mach 13.6 using the NASA–Air Reserve Component 100-MW arc facility, now mothballed. A second long-term alternative is a radiatively driven wind tunnel being investigated under the MHD Accelerated Research Into Advanced Hypersonics program. This facility relies on energy addition (through a combination of e-beam and MHD acceleration) in the supersonic portion of the facility flow expansion process. This facility concept is in the early stages of fundamental investigation, and significant questions exist concerning the flow quality that can be ultimately achieved. Continued investigation into this approach will be required to determine its ultimate capabilities.

See Chapter 9 for recommendations regarding the timing of key decisions regarding the ground-testing infrastructure.

Chapter 8

Recommended Management Approach

8.1 Organizational and Investment Concepts

An integral part of developing the hypersonic technology plan is, in addition to the identification of technology projects, the identification and assessment of investment and organizational concepts. This chapter briefly discusses the status, identifies options of the Air Force's hypersonic technology development activities, and recommends a management approach.

8.1.1 Current Situation

The status of the management of existing hypersonic technology programs can be described as a flock of several types of birds flying in a very loose formation. Due to the commitment and diligence of the people working on these programs, there are excellent informal communications and the sharing of plans and technical information. The AFRL HyTech scramjet development program will be completed in FY05. The DARPA ARRMD hypersonic missile technology demonstrator program, built around the AFRL HyTech engine, is proceeding aggressively and is scheduled to complete the flight test of several Mach 6.5 technology demonstrator missiles in 2003. The NASA X-43A hydrogen-fueled flight demonstrator program is scheduled to start flight-testing this year and will be completed in 2002.

Within the Air Force, rigorous system engineering and analysis of potential future hypersonic systems is sorely lacking. Technology development is proceeding without a requirements-driven systems engineering process, including modeling and simulation, formal trade studies, and the other analyses needed to establish technology development requirements and priorities. This is a very serious deficiency that is described explicitly in the 1998 NRC hypersonic study. The problem has not been corrected for space launch. No post-EELV hypersonic RLV systems engineering activities (such as mission analysis, system concepts development, and preliminary cost assessments) are being performed. This deficiency has not been corrected by Air Force Materiel Command or any of its component organizations. Our recommended approach to correcting it is addressed in Section 8.4.

The current Air Force hypersonic technology program at AFRL is limited to a small-scale, expendable scramjet engine development. Although this is largely due to inadequate S&T funding, it is also the result of not having a full-time technical system integration function.

While there is a high level of coordination and collaboration between some programs, the overall hypersonic research area of both DoD and NASA is not well coordinated or integrated. An example of strong coordination and collaboration is the Air Force HyTech and DARPA ARRMD program relationship. In this case, the AFRL focused its scarce resources on the ground development and demonstration of hypersonic airbreathing missile propulsion while structuring the program to feed the results to the DARPA ARRMD program. The ARRMD program depends solely on the HyTech Program for propulsion development. In addition to the strong AFRL/DARPA collaboration on ARRMD, the NASA Hyper-X program has also provided consulting services and testing to the ARRMD program. Within NASA, coordination between programs has been weak but is improving. An example is the inclusion of a Hyper-X follow-on, the X-43B, in the planning for Generation 3 research aircraft, led by the Marshall Space Flight

Center. In addition, in many cases, while there are common top-level goals, there is little or no agreement between the various performing organizations as to the “right” approach to achieving these goals. In summary, there is much room for improvement over the current status.

8.1.2 Hypersonic Technology Development Options

The Air Force has a number of options regarding the development of hypersonic technology and systems.

8.1.2.1 Status Quo

With the completion of the HyTech Program in 2005, AFRL’s hypersonic technology program, according to the planned S&T budget for the next several years, will be at a subcritical level. At this minimal level of investment, the US Air Force hypersonic development effort will be far below the level of effort in Russia, France, and Japan, and probably well below the level of effort in China and India. The only real value of maintaining the status quo is to retain the few AFRL scientists and technologists who have a demonstrated competence in hypersonics.

8.1.2.2 Stop and Start

The Air Force could stop the current hypersonic program, accept the consequences, and restart it when and if a future application is so compelling that it justifies the investment. This has been the traditional mode for hypersonics, starting with the original aerospace plane, continuing with the X-24/*Dyna-Soar*, and most recently with the National Aerospace Plane. According to historian Clarence J. Geiger, the *Dyna-Soar* cancellation “undoubtedly set back the pursuit of lifting reentry technology in the United States by at least a decade.”¹² Another paper, by Lt Col Bill Sullivan, NASP Testing Division, stated that it took \$200 million and 12 years to get hypersonic test facilities, which had been closed by the aerospace plane stoppage, back up to efficient operation.

Besides the traditional inefficiencies associated with stopping and restarting programs, there are some new effects. Funding for civil service salaries and for “overhead functions” (for example, the director’s staff) is now included directly in a program’s S&T funding line. Short-notice stoppage of programs has two unintended impacts: First, other programs are reduced because salary cannot be eliminated quickly. Second, a lengthy reduction in force is started where the young and talented but junior staff is lost, the most experienced are retired, and the resource is rarely restored. Moreover, while Lt Gen Bruce Carlson, J-8, stated to the SAB on 29 March 2000 that he did not support eliminating S&T in hypersonics, zeroing of the HyTech budget in FY00 did just that for airbreathing hypersonics.

8.2 Program Management Options

8.2.1 IHPTET Organizational Model

The Air Force could model hypersonic R&D after the very successful IHPTET program. IHPTET provides the propulsion technology base for all military aircraft. The program is viewed by many as a model program within DoD and has been very successful in getting technology into both military and commercial jet engines on a sustained basis. The goal of the

¹² *The Hypersonic Revolution*, Vol. I, ed. Richard Hallion, Bolling Air Force Base, DC: Air Force History and Museums Program, 1998, p. II-xviii.

IHPTET is to double aircraft and missile propulsion performance while decreasing manufacturing and maintenance costs by 35 percent by 2003 (compared with the 1987 baseline). The goals are further quantified by phases (I, II, and III) and by engine type (turbofan/turbojet, turboshaft/turboprop, or expendable). The team is organized in the following manner: The steering committee is composed of personnel from the Army, Navy, Air Force, DARPA, and NASA, with advisors from five propulsion companies. Component technology panels have been formed for demonstrators, combustors, exhaust systems, mechanical systems, fans or compressors, turbines, and controls. Pervasive technology panels covering materials, CFD, structures, and cost reduction have also been formed. Each of the industry advisors has at least one technology demonstrator engine. Each potential project is judged by four basic questions:

- What are you trying to do? (goals)
- When will it be accomplished? (pace of program)
- What difference will it make? (payoffs)
- What makes you think you can do it? (goals, objectives, technical challenges, and approaches [GOTCHA] process and financial scrub)

COMPRESSION SYSTEMS PHASE III TECHNICAL PLAN

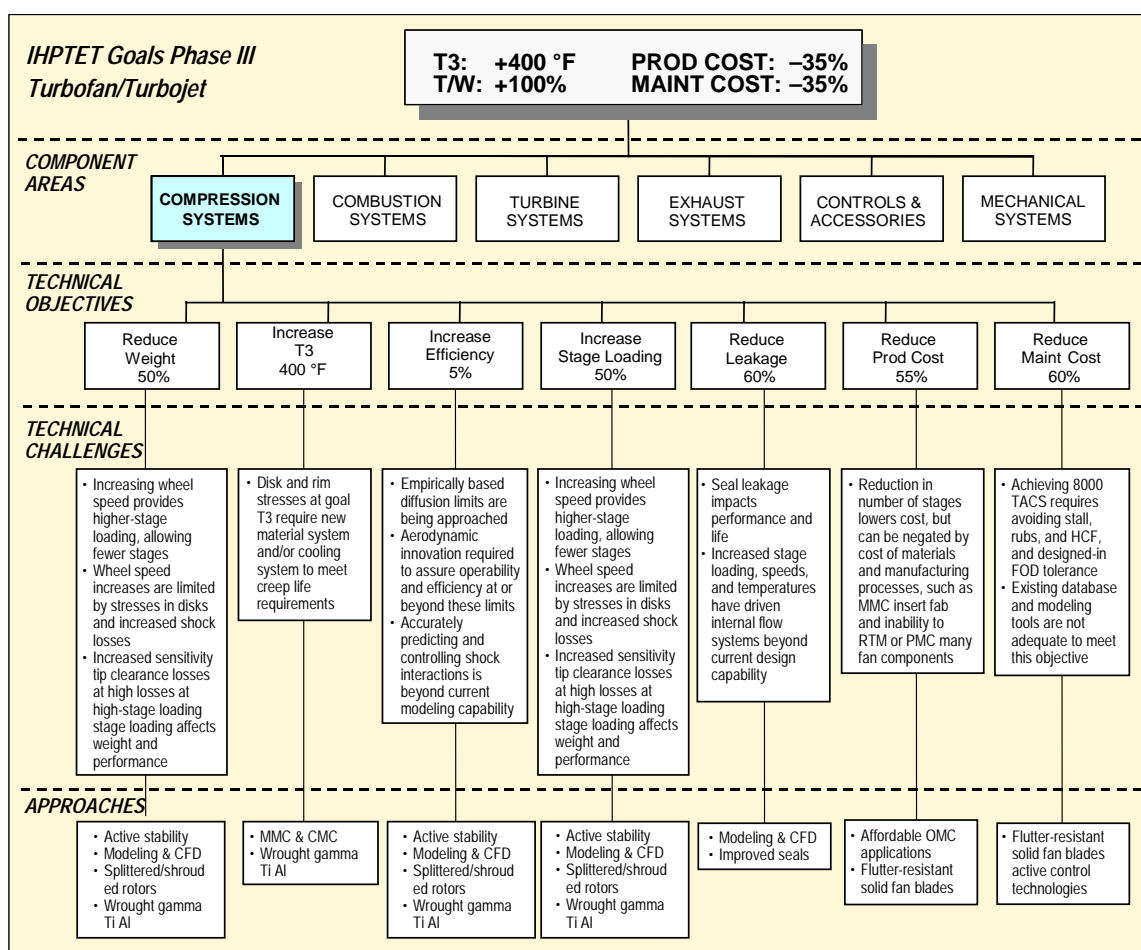


Figure 50. GOTCHA Chart Example

The GOTCHA process is traceable from goals, to objectives, to technical challenges, and finally to approaches (see Figure 50). The process takes component technologies, applies them to engine demonstrators, and quickly transitions them to operational aircraft. Over the whole program, funding percentages are broken down as follows: industry, 51 percent; Air Force, 34 percent; NASA, 6 percent; Navy, 5 percent; Army, 3 percent; and DARPA, 1 percent. IHPTET has been strongly advocated in the Services, the Office of the Secretary of Defense, and Congress.

8.2.2 Army-NASA Rotorcraft Model

Rotorcraft S&T activities in the United States have benefited from the long-standing partnership between the Army and NASA. The Army has experienced a unique relationship with NASA as a result of the 1965 agreement for joint participation in aeronautical technology related to Army aviation. A master agreement between NASA and the Army covers research activities at three NASA research centers (Ames, Langley, and Glenn). Individual agreements executed between the lead Army activity at each center and the local NASA center director define the specific operating relationships at each center. An important side benefit of this arrangement is that it facilitates the transfer of aeronautics-related technology from the NASA centers to nonaviation Army vehicles.

The basic premise of the agreements is that, through the integration of R&D resources, the Army can leverage NASA research facilities and expertise while NASA benefits from Army expertise and the Army's requirements for real-world applications to enhance the relevance of NASA research programs. The agencies also combine financial resources to obtain critical mass on programs of common interest. Army assets are placed at the NASA centers where there are unique facilities and expertise that can go the furthest toward meeting Army technology requirements. Through the development of integrated programs, a dual-use focus on the technology is assured, and duplication of effort can be avoided with relative ease. The Army's lead role within DoD for the development of rotorcraft technology makes this even more effective. Personnel from either agency can be placed in joint work environments, under either NASA or Army leadership, and technical supervision is provided by the best-qualified personnel from either agency. The Army director at each center also helps to establish interaction between the centers and other Army organizations.

The Army pays no direct rent for the occupation and use of NASA facilities under the agreements. Administrative support is provided through Army personnel working within the NASA structure to assist in meeting both the Army's and NASA's needs. This joining of support activities results in an economy of scale that benefits both organizations. A major benefit is that the Army personnel, in their mission to support the Army Aviation Program Executive Officer, individual aviation system program managers, and other Army organizations, have high-priority access to NASA facilities and the expertise to address developmental and fielded systems problems (for example, the "911 call"). NASA also has direct access to Army research scientists who can apply their expertise to overcome technology barriers limiting the commercial viability of modern civil rotorcraft.

The interaction of the aviation element of the Army with NASA continues to provide an integrated national program in rotorcraft technology, which benefits significantly by the contributions of both agencies. The integration of the best scientists and engineers in the

Government to pursue the technologies focusing on multiple applications is an excellent example of what interagency cooperation and shared programs can accomplish. Successful collaboration requires accepting challenging requirements that can benefit a variety of customers and sharing credit for meeting national needs. Working arrangements where joint activities are recognized and credit is shared are vital if the not-invented-here syndrome, a major contributor to duplication and loss of productivity, is to be overcome. The Army has been working successfully with NASA on this basis. One of the drivers for program success has been the management technique used by the Army in approaching the implementation of the agreement. The integration has been accomplished by starting small in each interaction and working with NASA to develop a strong integrated program.

This is one model of an integrated aeronautics S&T program. It serves as an example of what can be accomplished when two organizations join forces to focus on common goals. It should be noted that this relationship did not materialize overnight. The NASA-Army Joint Agreement has been in place since 1965, and the way in which it functions is not always readily understood by individuals who have not worked within it. The principal requirement for making such a partnership work is a common vision of attaining an important national goal that is strong enough to overcome the traditional tendencies to strive for individual control and recognition.

In summary, the rotorcraft community has benefited from 35 years of forging the relationships that enable an integrated approach to the planning and execution of a national dual-use rotorcraft S&T program. The NASA-Army partnership continues to make this possible. A similar model could be established for an integrated Air Force–NASA hypersonics research program.

8.2.3 Public and Private Partnerships

Conceptually, the recommended hypersonics development program offers a rich opportunity for government-industry partnerships. However, no partnership can be established that does not offer industry the opportunity ultimately to achieve profits that justify its investment of money and other corporate resources in the partnership. The US investment community is currently much less favorable to space launch and satellite systems investments than it was a few years ago. The financial failure of the Iridium commercial communications satellite program has been one major factor causing this much more cautious approach to these types of investments.

Conceptually, the most likely attraction for a corporate investment would be to be offered a fixed-price reusable space launch vehicle in return for a specified investment in the hypersonic RLV development program. This would raise a number of complex contractual issues—not impossible to resolve but certainly difficult. Despite the probable difficulties, it is likely that a small number of corporations will be very motivated to invest in the program once it is firmly established and ready to enter a reasonable-risk EMD program.

8.3 International Options

The United States must ensure that any international hypersonic technology development activity undertaken is in its best interests. Special consideration must be given to technologies that can be applied to weapons and technologies that lead to a significant competitive edge. International options for hypersonic technology development can include joint and contracted activities. Past efforts have been focused on the contracted one-way transfer of hypersonic technologies from Russia to the United States. Examples include endothermic fuels (Air Force), facilities research

(NASA), and the Mach 6 scramjet flight test (NASA). While the potential for a future international joint program in hypersonic space launch vehicle development exists, it is most likely not near term. Moreover, due to the difficulty in executing a joint international program (for example, the International Space Station), any proposed program would have to be critically examined to ensure that it is in the nation's best interests. At the present time international collaboration is best conducted at the 6.1 and 6.2 technology development levels, as has been and is being done with Russia and other countries.

AFRL also has an active cooperative data exchange agreement with France, including joint ramjet development activities and an ongoing fuel-cooled scramjet engine wall project.

8.4 Recommended Management Approach

This recommended management approach is based on the conclusion that an integrated Air Force–NASA program is essential to achieving the hypersonic technology and systems development objectives recommended by this study. This approach is, to a large degree, based on the NASA–Army Rotorcraft model and the tri-Service IHPTET programs previously described. The management objective is to successfully achieve the phased technical and program objectives stated in the Investment Roadmap section (see Chapter 9) of this report.

8.4.1 Program Management Agreement

The first step will be to prepare an Integrated Hypersonics Program Management Agreement for approval by the Secretary of the Air Force and the Administrator of NASA that addresses each of the following topics:

- Program objectives
- Program roadmap
- Hypersonics Steering Committee
- Program management
- Air Force responsibilities
- NASA responsibilities
- Army, Navy, DARPA, and other government interfaces
- Industry participation
- University participation
- Air Force–NASA senior management oversight

8.4.1.1 Integrated Hypersonics Program Organization

The overall program organization (see Figure 51) is based on selecting proven solutions developed by the Army–NASA Rotorcraft model and the tri-Service IHPTET program previously described. The steering committee would meet annually with the Secretary of the Air Force and the NASA Administrator to review program objectives, accomplishments, issues, and any significant revisions to the overall program roadmap.

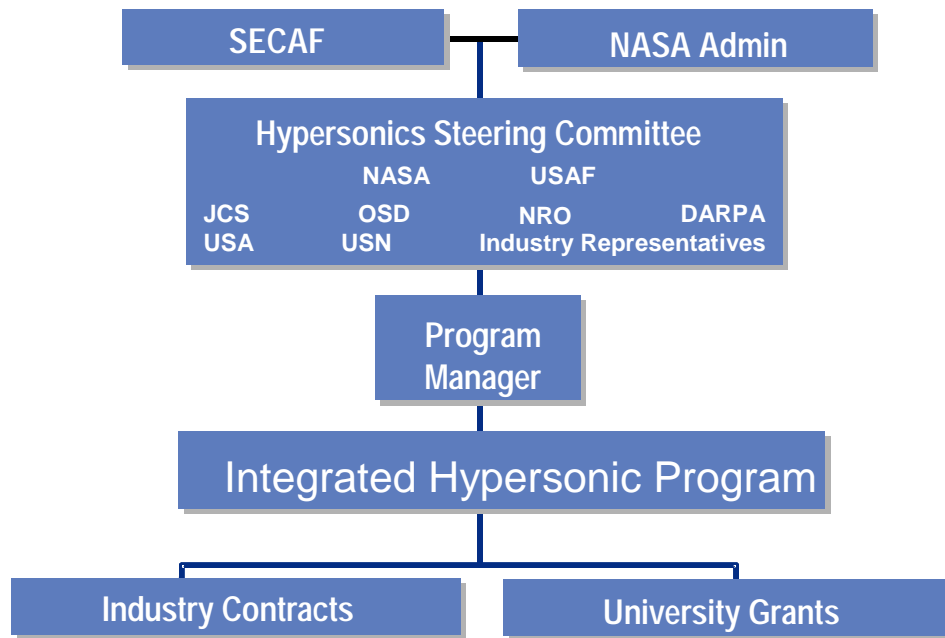


Figure 51. Program Organization

8.4.1.2 Hypersonics Steering Committee

The primary responsibility of the steering committee is to establish technical objectives and priorities and independently evaluate technology development status and issues. All committee members must have extensive knowledge of hypersonic technology and have a strong personal commitment to achieving the objectives of the planned integrated hypersonic technology program. The following membership is recommended:

Principal Partners

- US Air Force
- NASA

Other Participants

- NRO
- US Navy
- US Army
- DARPA
- Director, Defense Research and Engineering

Meeting Participants (not voting members)

- Aerospace industry contractors
- Selected university representatives

The position of committee chair and deputy chair would be rotated every 2 years between the Air Force and NASA, such that an individual would serve 2 years as deputy chair and then 2 years as chair.

Based on IHPTET program experience, the personal commitment and mutual trust of this committee will be the major factor in the success of the integrated hypersonics program. The role of the chair, as described by experienced IHPTET participants, is to run a “benevolent dictatorship.”

The committee would meet quarterly, and the meetings would be conducted on a rotating basis at Air Force, NASA, and other facilities where the most significant hypersonic technology development activities are taking place. The most important continuing function of the steering committee is to establish, sustain, and nurture the accomplishment of common goals.

8.4.1.3 Program Management Approach

A small, joint system program office should be established, headed by an experienced program manager and including a chief systems engineer. It is essential that this program office have a strong technical management focus, not a financial and administrative focus. The program manager would be required to present a comprehensive program status and issues briefing to the steering committee quarterly. The program office would have no contracting responsibilities. All contracting would be done by existing Air Force and NASA contracting offices.

8.4.1.4 Air Force and NASA Program Staffing

Initial program staffing would be drawn primarily from the existing hypersonic technology staffs of the Air Force at AFRL and NASA at LaRC. Once an integrated hypersonic technology work breakdown structure is established and approved by the steering committee, Air Force and NASA staffing would gradually evolve to meet the needs of the program. Support contractors would be used as required.

8.4.1.5 Industry Participation

Each major aerospace corporation that decides to participate in the hypersonic space launch vehicle program should attend the steering committee meeting for several reasons. The most important one is to focus industry independent research and development in hypersonics in the most important technical areas. Developing hypersonic technology is not currently a high-priority activity in major US aerospace companies. However, this will change if the Air Force and NASA initiate the recommended integrated hypersonic development program leading to a hypersonic space launch system.

8.4.2 Recommended Short-Term Action Plan

To implement the recommended management approach for achieving a hypersonic space-access system by 2025, the Air Force, in conjunction with NASA, should take the following actions by 30 June 2001:

1. Prepare the Air Force–NASA Integrated Hypersonics Program Management Agreement and obtain the approval of the Secretary of the Air Force and the NASA Administrator.
2. Appoint the Hypersonics Steering Committee and select a chair and deputy chair.

3. Appoint the Program Manager, Air Force–NASA Integrated Hypersonics Program, and Chief Systems Engineer.
4. Conduct industry briefings to focus independent research and development efforts on high-priority objectives of the integrated Air Force–NASA program.
5. Issue a comprehensive announcement to universities describing the technical and schedule priorities of objectives of the program.
6. Prepare jointly with NASA Phase 1 budgets (see Chapter 9) that provide Air Force and NASA funding for the integrated hypersonic development program. Plan budgets for Phase 2 and beyond.

8.4.3 Systems Requirements and Systems Engineering

An obvious essential ingredient of the recommended hypersonic program is for AFSPC to initiate the formal requirements and CONOPS development process and for Air Force Materiel Command to establish the formal systems engineering responsibility and plan the appropriate staffing. The Air Force–NASA integrated program manager must have a small staff of senior systems engineers provided by Aeronautics Systems Center (ASC), SMC, and NASA. A high-level systems engineering roadmap is included in Chapter 9.

Within the Air Force, there has been confusion about which product organization should have responsibility for hypersonics. ASC has tools and processes to analyze and perform trades on atmospheric vehicles. The primary purpose for such a vehicle is space access—an area in which SMC has responsibility. One of these organizations should be assigned clear leadership and overall responsibility, and the other should support as appropriate.

8.4.4 Integration of Related Air Force 6.1 S&T Program

The Air Force 6.1 S&T program, funded at \$6 million per year, must be evaluated to assure that the proper priority is being given to technology critical to a hypersonic RLV program. These priorities should be reviewed and approved annually by the Hypersonics Steering Committee. Obviously these priorities should be communicated to the relevant academic community. This SAB study did not assess the current priorities in this area of Air Force S&T.

8.4.5 Integrating and Focusing the Small Business Innovative Research (SBIR) Program

The Air Force is not taking advantage of the potential for the SBIR program to make significant research contributions to the hypersonic technology base.

A strategy based on integrating SBIR awards into the overall hypersonics S&T technology program is recommended. This would be executed by

1. Identifying key technical issues that could be resolved by entreprenuring small businesses while meeting the criterion of potential commercialization
2. Including descriptions of the technical challenges in the topic areas that are posted in the annual announcement for proposals from the Director, Defense Research and Engineering
3. Setting aside 5 to 10 Phase 2 awards in hypersonic technology annually
4. Integrating the SBIR activity into the overall S&T program during the contract period

Potential R&D areas are

1. A user-friendly PC-based performance code, capable of assessing competitive vehicle and propulsion systems
2. Innovative inlet designs for bifurcated hypersonic engine flowpaths
3. Innovative techniques for pulse-starting of overly contracted inlets
4. New techniques for the ignition and flame stabilization of storable fuels in dual-mode ram-scramjet engines
5. Low-cost ejector and injector motors for RBCC engines
6. Catalysts for accelerating and controlling the thermal decomposition of endothermic fuels
7. Methods for implementing base burning to reduce or eliminate transonic base drag on hypersonic vehicles
8. Development of health-monitoring systems for hypersonic vehicles
9. Catalysts to accelerate three body recombination reactions in hypersonic exhaust nozzles

8.5 Conclusions and Recommendations

This hypersonic development program requires significant financial, human, and facility resources that can be best provided by an integrated Air Force–NASA effort. This is the most promising approach for the United States to become the 21st-century leader in the development and military exploitation of hypersonic technologies and systems.

Chapter 9

Investment Roadmap

9.1 Technology Development

9.1.1 Overall Investment Roadmap

Hypersonic programs have suffered in the past from highly turbulent funding, lack of integrated system development, and rigorous system engineering. The integrated Air Force–NASA program roadmap shown in Figures 53 (long-term) and 54 (near-term) will correct these deficiencies. When it is implemented, it will provide the continuity of funding, results-based system development, and concurrent systems engineering required to investigate and select critical enabling technologies while maintaining critical personnel skills and industrial capabilities. We believe that this roadmap is the rational path for the Air Force to achieve a reusable military space-access vehicle by 2025. A key factor that has limited the nation’s ability to sustain development of hypersonic systems has been the lack of flight-test data. The recommended program contains the flight demonstrations required to support technology decisions by providing data for design analysis and modeling and simulation development. Concurrent system engineering is an integral part of the program. The program described below contains the components required to answer the tough scientific and engineering questions that support the Air Force’s and NASA’s access-to-space programmatic decisions. The program is divided into four phases. Each phase has clearly defined exit criteria as discussed in Sections 9.1.3 through 9.1.6.

9.1.2 Systems Engineering Approach

A critical ingredient for success of the overall hypersonic technology development and demonstration effort is the planning and execution of a continuous series of rigorous system-level studies and analyses. The studies and analyses must provide the technical basis for the assessment and selection of configurations and technology alternatives and options. These activities should not be confused with what some consider to be an administrative or technical management function. Rigorous systems engineering can be defined as the basic technical work required to invent, assess, and decide technical options and alternatives. A high-quality technical team to perform the required systems engineering must be established to ensure the success of the proposed hypersonic program.

Figure 52 summarizes selected major systems engineering tasks, which must be accomplished during each phase of the recommended four-phase hypersonic development program.

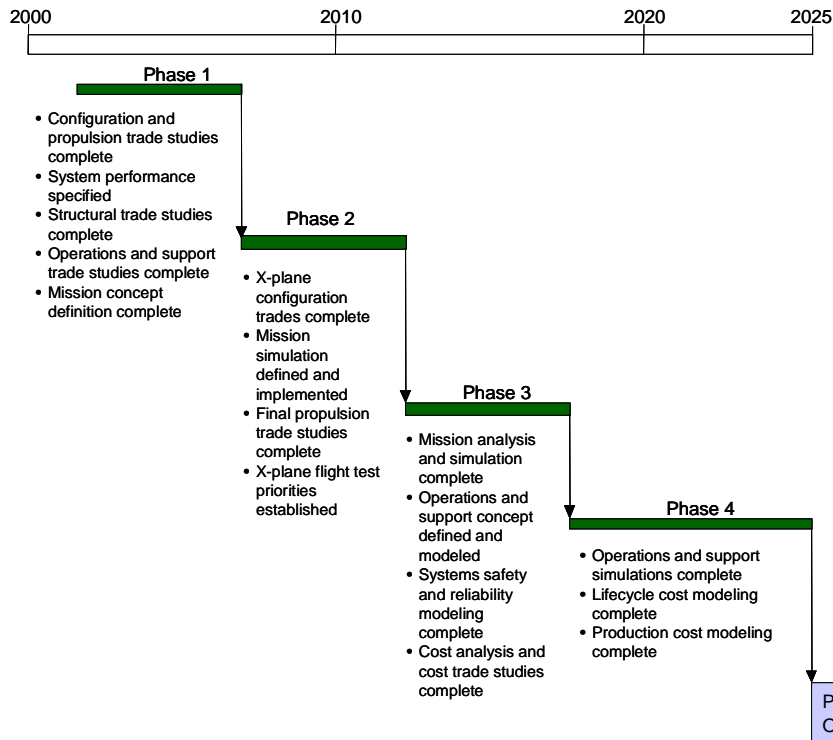


Figure 52. Systems Engineering Roadmap

9.1.3 Phase 1: Technology Development and System Configuration Assessment

The Technology Development and System Configuration Assessment phase lasts approximately 4 years—from 2003 to 2007. This phase results in the development of the key enabling hypersonic technologies and the determination of the technical and financial feasibility of a hypersonic space launch system. A more detailed view of Phase 1 is shown in Figure 54. In this phase, results from the ongoing NASA Hyper-X, DARPA ARRMD and Air Force HyTech programs, coupled with flight and combined-cycle demonstrations and staging investigations, feed the system configuration selection. The completion of the ARRMD program and available data from the program support a missile option go-ahead decision in 2003. Technical questions regarding the takeoff mode, propulsion system, system architecture, and overall vehicle design will be answered in Phase 1.

At the top of Figure 53 are milestones representing the NASA decisions for Generation 2 and 3 systems occurring in approximately 2005 and 2015, respectively, as well as the Generation 3 First Demo Engine and X-Plane decisions. These NASA decisions are important to the integrated program. By national policy agreement, the Generation 2 decision defines the next-generation RLV space-access system on which the Air Force will be depending until at least 2025. The Generation 3 decision affects the follow-on generation of RLVs to be developed and fielded later in the century.

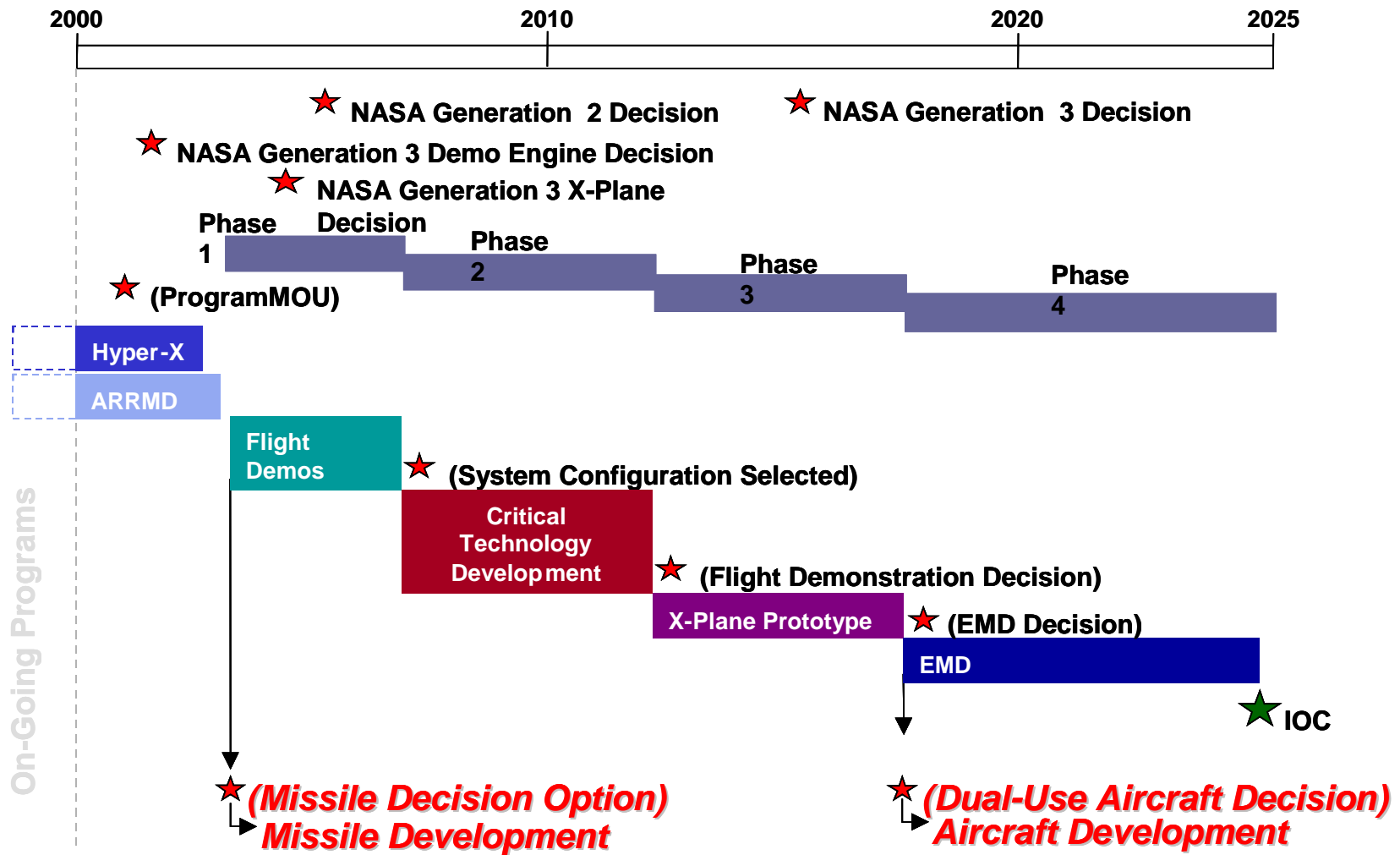


Figure 53. Long-Term Program Roadmap (FY00 to FY25)

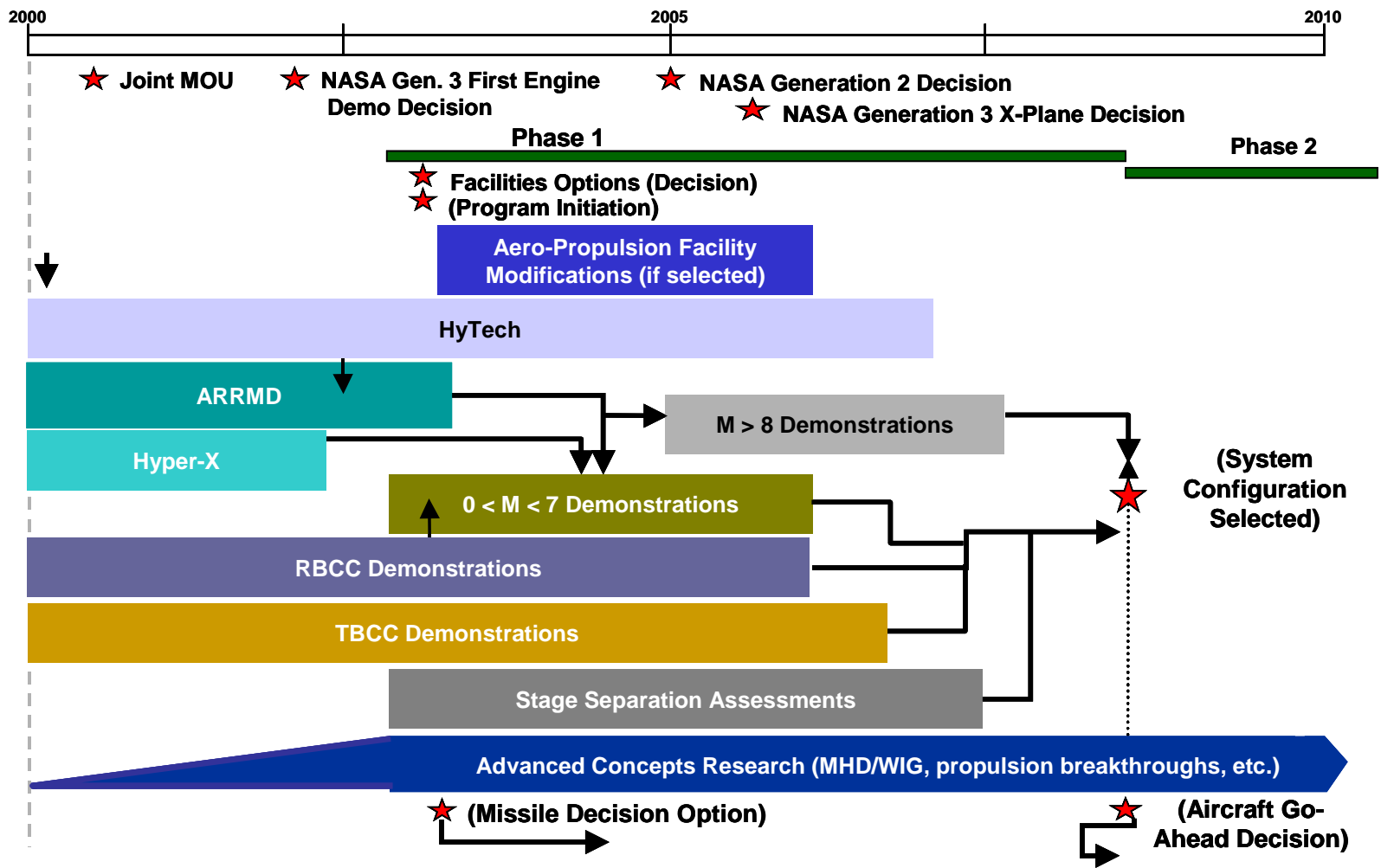


Figure 54. Near-Term Program Roadmap (FY00 to FY10)

9.1.3.1 Aero-Propulsion Facility Investment Strategy

The proposed hypersonic program requires extensive ground- and flight-testing to provide much-needed data to answer science and engineering questions regarding propulsion, fuels, thermal structures, and airframe-engine integration. NASA and the Air Force have many ground-test facilities, but additional capabilities may be required. The decision on the scope and direction of the required facilities upgrades is the second major decision shown on the program roadmap (see Figures 53 and 54).

Existing facilities can support propulsion performance testing up to approximately Mach 7. Higher Mach numbers can be tested only for a very short duration (milliseconds). Current facilities can test integrated airframes between Mach 0 and 3 for long periods (minutes). New facilities could support higher Mach number propulsion testing for seconds at a time and integrated-airframe testing for minutes. There is a clear synergy between the data analysis accompanying the Phase 1 flight tests and the facility modifications. The flight-test data will help validate results from the ground-test facilities and affect further modifications and improvements.

There are opportunities for improved Air Force test capabilities ready to submit for approval for Air Force military construction funding in the near term. These facilities would significantly accelerate the S&T program and ultimately the development of hypersonic vehicles. They include the conversion of a rocket test stand to an RBCC test stand at AFRL Edwards, restoration of AEDC Aerodynamic Propulsion Test Unit testing capability, and the fabrication and installation of supersonic freejet nozzles in the AEDC Aeropropulsion Systems Test Facility.

9.1.3.2 Phase 1 Exit Criteria

Technical

- System performance requirements established
- System modeling and simulation implemented and operational
- Operational system concept selected, and enabling technologies identified
- Takeoff mode
 - Propulsion system
 - Structural architecture
 - Stage separation Mach and altitude
 - Systems and subsystems
- Detailed ground-test plan and schedule established

Management and Financial

- Preliminary cost estimates for Phases 2, 3, and 4, and the preliminary estimate of operations and support costs completed
- Program plan and schedule for Phase 2 completed
- Program management organization and staffing for Phase 2 established

9.1.4 Phase 2: Critical Technology Development and Demonstration

The Critical Technology Development and Demonstration Phase lasts approximately 5 years—from 2007 to 2012. This phase results in an X-Plane preliminary design, ground testing (large- and full-scale) of the selected propulsion system, other critical technology demonstrations, and a bottom-up EMD cost estimate.

It is clear that enabling technologies, especially regarding the propulsion system, are vital to the program. Phase 2 of the program further develops these critical technologies for inclusion in the X-Plane prototype. Analysis of ground- and flight-test data will support X-Plane design through the preliminary design review.

9.1.4.1 Phase 2 Exit Criteria

Technical

- High-fidelity modeling and simulation of the total X-Plane system completed
- Selected propulsion system successfully tested to the limits of ground testing
- Preliminary X-Plane flight-test plan completed
- Preliminary design review of X-Plane completed

Management and Financial

- X-Plane program plan and schedule completed
- X-Plane program organization and staffing defined
- X-Plane program cost estimates completed
- Preliminary cost estimates of EMD and operations and support developed and substantiated

9.1.5 Phase 3: X-Plane Design, Manufacturing, and Flight Testing

The X-Plane design, manufacturing, and flight-testing phase lasts approximately 6 years—from 2012 to 2018. This phase results in a complete X-Plane final design, fabrication, and ground- and flight-test program, including the identification of all technical deficiencies supporting the EMD RLV design.

Phase 3 of the program is critical because known remaining technical questions will be answered and the trades made before the EMD RLV is defined. Ground testing, flight testing, and system concepts must be completed during this phase. A dual-use aircraft go-ahead decision can be made at the end of Phase 3.

9.1.5.1 Phase 3 Exit Criteria

Technical

- Mission analysis of the operational system completed
- Preliminary concept of system operations and support defined and modeled
- Ground testing, including reliability testing of all critical functional subsystems completed
- Flight-test data demonstrate readiness for EMD
- Preliminary design and analysis of the EMD vehicle completed

Management and Financial

- EMD, production, and operations and support cost estimates completed and substantiated
- EMD integrated master plans and schedules completed
- EMD program management plan, program organization, and key personnel selection completed

9.1.6 Phase 4: Engineering and Manufacturing Development

The EMD phase lasts approximately 7 years—from 2018 to 2025. This phase results in a thorough ground- and flight-test program in which all deficiencies have been corrected. Operational policies and procedures have been defined and validated. A complete production plan and associated cost estimate will be developed.

9.1.6.1 Phase 4 Exit Criteria

Technical

- All ground testing completed: structural, environmental, reliability, maintainability, etc.
- Flight testing successfully completed
- All design changes for production completed
- All operational and maintenance technical data completed and validated

Management and Financial

- Production plan, schedule, and budget established
- Operations and support cost estimates finalized
- Operational and maintenance organization and staffing finalized

9.2 Personnel and Industrial Base Development

There is a serious shortage of experienced technical personnel in the high-speed flight area, especially hypersonics. The cyclical funding cycle and uncertain future of new funding, coupled with the difficulty of the technical disciplines, have discouraged people from working in the high-speed field. In the large engine and aircraft development companies, downsizing has also eliminated many positions. Government organizations working in hypersonics, especially AFRL, have experienced reduced funding and seen a dramatic departure of young, promising engineers and scientists. It is clear that foreign organizations, especially in Russia, France, and Japan, are supporting stable, sustained state-of-the-art research, which keeps research teams active and motivated.

To reduce the hemorrhage of young talent and replace an aging science and engineering workforce, it is necessary to take the following actions now:

- Retain key government research leaders by maintaining funding levels that produce real research and leadership opportunities
- Maintain modern research facilities that support state-of-the-art investigations
- Provide funding to academic institutions to invigorate hypersonic research in key colleges and universities
- Support contracted efforts with private industry and encourage innovative cost-sharing approaches until adequate funding sustains the research efforts

9.3 Costs and Budget

The estimated cost of the program by phase is shown in Table 3.

Table 3. *Annual Program Costs by Program Phase*

Annual Funding (\$M)	Joint Program Phases					
	FY01 and FY02	Phase 1 FY03	Phase 1 FY04–FY06	Phase 2 FY07–FY11	Phase 3 FY12–FY17	Phase 4 FY18–FY24
Air Force	6	18	30-40	150-200	300-400	400-500
NASA	30	30	30-40	150-200	300-400	400-500
Total/Year	36	48	60-80	300-400	600-800	800-1,000

Phase 1 Major Investment Areas for Technology Development and System Configuration Assessment

Major Task	Percent Investment
Mission Analysis	2
System Concept Development and Propulsion System Selection	5
Supportability	3
Propulsion Technology	57
Structures and Materials	21
Thermal Protection	5
Navigation, Guidance, and Control System Definition	2
Other Critical Technology	5

Phase 2 Major Investment Areas for Critical Technology Development and Demonstration

Major Task	Percent Investment
Propulsion System Design and Analysis	6
Supportability	3
Propulsion System Manufacturing	58
Test System Design and Construction	4
Other Critical Technology Development and Demonstration	13
Ground Testing	10
Program Support	4
Mission Analysis and Definition	2

Phase 3 Major Investment Areas, X-Plane Design, Manufacturing, and Flight Testing

Major Task	Percent Investment
Supportability	2
Mission Analysis and EMD Program Definition	5
X-Plane Design and Analysis	14
X-Plane Manufacturing (2 vehicles)	43
Ground Testing	8
Flight Testing	18
Program Support	10

Phase 4 Major Investment Areas, Engineering and Manufacturing Development

	Percent Investment
Engineering Design and Analysis	25
Manufacturing, Engineering, and Tooling	6
Production (3 vehicles)	38
Ground and Flight Test	25
Program Support	6

9.4 Hypersonics Investment Decision Roadmap

The SAB recognizes that this hypersonic development program must have formal decision points and that, due to the program's magnitude, each phase will require formal critical review and approval by the Secretary of the Air Force, the Chief of Staff, and NASA Administration. The program has been structured to enable this decision-making process, as depicted in Figure 55.

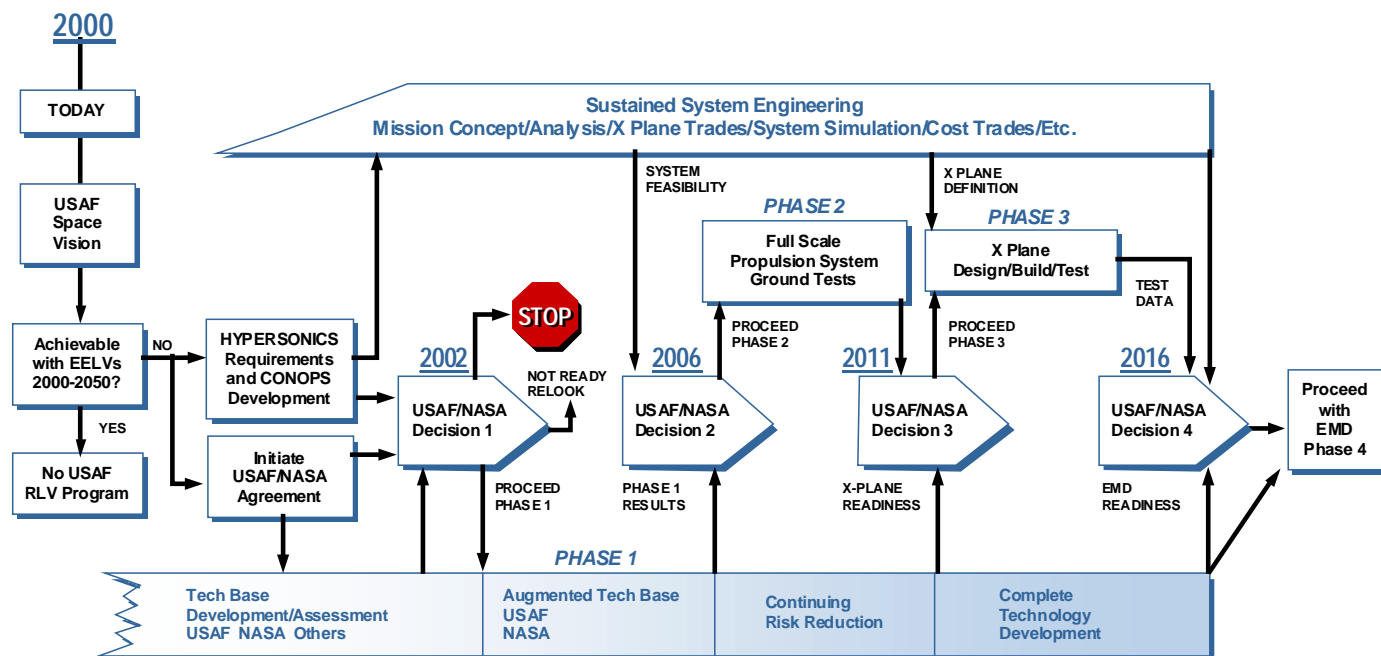


Figure 55. Hypersonics Investment Decision Roadmap

9.5 Conclusions and Recommendations

The United States has no current plan to be the world leader in the development of hypersonic technology and airbreathing hypersonic spacelift and weapon systems in the 21st century. Without a plan, the Air Force will not achieve its vision of an aerospace force. Implementing the recommended program roadmap would be a major step toward achieving this objective.

Chapter 10

Policy Requirements

The National Space Policy promulgated by the NSTC in 1996 is broad enough to permit a number of alternative RLV development strategies. Only a focused military RLV development program—independent of NASA—would require consultation with the White House Office of Science and Technology Policy and notification of Congress to change the existing policy. However, a joint Air Force–NASA RLV development program should not require changes to the National Space Policy.

The spectrum of alternatives and associated policy implications include the following:

- The Air Force buys launches and services from the NASA-commercial fleet. Implicit in this scenario is that NASA maintains the lead on RLV development, and DoD neither develops nor procures a unique military RLV. In this case, no changes to existing policies are needed.
- The Air Force procures a few RLVs from commercial suppliers. As in the previous scenario, the Air Force does not independently develop an RLV, but rather buys and operates RLVs developed by the private sector. This case is analogous to procuring commercially developed ELVs. Again, no changes to the existing policies are necessary.
- The Air Force provides NASA with military-unique requirements during the R&D phase and pays for military models and testing. This scenario extends only through the R&D phase and does not include the development of an operational military RLV with potentially unique characteristics from a commercial or civil RLV. The scenario falls within the bounds of existing policies and does not necessitate any policy revisions.
- Consistent with its vision, the Air Force develops an RLV with unique military capabilities for access-to-space and transatmospheric operations. Under the joint Air Force–NASA management structure proposed in Chapter 9, initial studies and R&D through EMD (Phases I to III of the Far-Term Program Plan) are consistent with existing policies and will therefore not require policy changes. However, the National Space Policy will need to be modified when the Air Force commences a separate program to develop a unique military RLV. As with the current policy, the NSTC will be responsible for developing the new policy, and the Office of Science and Technology Policy will lead policy implementation. In this case, coordination with NASA will still be required, and the technology developed under the Air Force program should be shared among the agencies. Likewise, the Air Force should incorporate dual-use technology to the greatest degree possible. The Air Force will need a separate budget line for development and procurement of its RLV.

In summary, the current National Space Policy is broad enough to encompass most development scenarios without modification. Should the Air Force decide, consistent with its vision of an aerospace force, to develop a military-unique RLV, the National Space Policy will need modification. Under the Far-Term Program Plan proposed in Chapter 9, these changes would not be necessary until 2015–2018.

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Chapter 11

Summary Recommendations

Concept Recommendations

- Develop mission and system concepts to meet the Air Force vision (AFSPACECOM)
 - CSAF review and approve
 - Publish appropriate statement(s) of operational requirements
- Assign either SMC or ASC clear leadership responsibility for air breathing hypersonics system engineering with the other supporting
- Develop an overall hypersonics roadmap and identify and schedule critical enabling technical decisions (SAF/AQ)
 - Use the SAB recommended program as a guide

Program Recommendations

- Join with NASA in an integrated program focused on answering the key technical questions on air breathing hypersonics (SECAF)
 - Include other Service and industry participation
- Insert a funding wedge starting in 03-04 into the 02 budget submission for a robust program that supports SPACECOM needs (SAF/AQ)
- Form a hypersonic technology team during FY01/02 to engage technically with the Air Force HyTech, the DARPA ARRMD, and the NASA Hyper-X flight demonstration teams (SAF/AQ)
 - Develop lessons learned and understanding
 - Offer in-house support as possible
- Continue to fund, at current levels, HyTech and selected hypersonic initiatives consistent with FY01-02 funding availability (SAF/AQ)
 - Projects should be realigned to support downstream critical decisions to the extent possible

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Appendix B

Recommended Reading

America's Air Force Vision 2020, www.af.mil/vision.

Hypersonic Applications and Technologies for USAF Laying the Groundwork for SAB Study on "Why and Whither Hypersonics Research in the USAF," AFRL-PR-WP-TR-2000-2114, Frederick S. Billig (Chairman), E. T. Curran, G. Keith Richey, Terence M. Ronald, Richard Weiss.

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Appendix C

Acronyms and Abbreviations

AAR	Air-Augmented Rocket
ABL	Airborne Laser
AEDC	Arnold Engineering Development Center
AFOSR	Air Force Office of Scientific Research
AFSPC	Air Force Space Command
AFRL	Air Force Research Laboratory
AHM	Airborne Hypersonic Missile
Al	Aluminum
ANSER	Analytic Services Inc.
ARRMD	Affordable Rapid Response Missile Demonstrator (DARPA)
ASC	Aeronautics Systems Center
ASSET	Aerothermodynamic/elastic Structural Systems Environmental Tests
atm	Atmospheres of Pressure
BMDO	Ballistic Missile Defense Organization
CAV	Common Aero Vehicle (USAF)
C ²	Command and Control
C ⁴ ISR	Command, Control, Communications, Computers, and Intelligence, Surveillance, and Reconnaissance
C-C	Carbon-carbon
CFD	Computational Fluid Dynamics
CINC	Commander in Chief
CONOPS	Concept of Operations
CONUS	Continental United States
CRAF	Civil Reserve Air Fleet
DARPA	Defense Advanced Research Projects Agency
DBT	Deeply Buried Target
DE	Directed Energy
DoD	Department of Defense
E/O	Electro-Optical
EELV	Evolved Expendable Launch Vehicle
ELV	Expendable Launch Vehicle
EMD	Engineering and Manufacturing Development
EMP	Electromagnetic Pulse
Fe	Iron
FOD	Foreign Object Damage
ft	Feet
ft/sec	Feet per Second
GEO	Global Engagement Operations
GOTCHA	Goals, Objectives, Technical Challenges, and Approaches
GTOW	Gross Takeoff Weight
H ₂ O ₂	Hydrogen Peroxide
HF/DF	Hydrogen Fluoride/Deuterium Fluoride
HOTOL	Horizontal Takeoff and Landing
HPM	High-Power Microwave
Hyper-X	NASA Hyper-X program (X-43)

HyTech	Hypersonics Technology Program (USAF)
ICBM	Intercontinental Ballistic Missile
IHPRPT	Integrated High-Payoff Rocket Propulsion Technology
IHPTET	Integrated High-Performance Turbine Engine Technology
IOC	Initial Operational Capability
ISR	Intelligence, Surveillance, and Reconnaissance
IW	Information Warfare
JCS	Joint Chiefs of Staff
JP	Jet Propellant
KE	Kinetic Energy
KKV	Kinetic Kill Vehicle
KT	Kiloton
kW	Kilowatt
lb	Pound
L/D	Length-to-Diameter
LD	Low-Density
LEO	Low Earth Orbit
lox	Liquid Oxygen
m	Meter
M	Mach
MGD	Magneto Gas Dynamic
MHD	Magnetohydrodynamic
MOU	Memorandum of Understanding
MTW	Major Theater War
MW	Megawatt
NASA	National Aeronautics and Space Administration
NASA LaRC	NASA Langley Research Center
NASP	National Aerospace Plane
Nb	Niobium
NHFRF	National Hypersonic Flight Research Facility
nm	Nautical Miles
NRC	National Research Council
nm	Nautical Miles
NRO	National Reconnaissance Office
NSTC	National Science and Technology Council
OSD	Office of the Secretary of Defense
PBD	Program Budget Decision
PDE	Pulse Detonation Engine
PRIME	Precision Recovery Including Maneuvering Entry
psi	Pounds per Square Inch
R&D	Research and Development
RBCC	Rocket-Based, Combined Cycle (Engine Configuration)
RCS	Radar Cross Section
RDT&E	Research, Development, Testing, and Evaluation
RLV	Reusable Launch Vehicle
S&T	Science and Technology
SAB	Air Force Scientific Advisory Board
SAM	Surface-to-Air Missile
SBIR	Small Business Innovative Research
SBL	Space-Based Laser
SBR	Space-Based Radar

scramjet	Supersonic Combustion Ramjet
SEAD	Suppression of Enemy Air Defenses
SECAF	Secretary of the Air Force
SLBM	Sea-Launched Ballistic Missile
SMV	Space Maneuvering Vehicle (AFSPC)
SOT	Statement of Task
SOV	Space Operations Vehicle (AFSPC)
SSTO	Single Stage to Orbit
TACS	Theater Air Control System
TAV	Trans-Atmospheric Vehicle
TBCC	Turbine-Based Combined Cycle (Engine Configuration)
TBD	To Be Determined
TBM	Theater Ballistic Missile
TCT	Time-Critical Target
TEL	Transporter-Erector-Launcher
THAAD	Theater High-Altitude Area Defense
Tgt	Target
Ti	Titanium
TSTO	Two Stage to Orbit
UAV	Unmanned Aerial Vehicle
USA	US Army
USAF	US Air Force
USN	US Navy
VHM	Vehicle Health Monitoring
W	Watt
WIG	Weakly Ionized Gas
WMD	Weapons of Mass Destruction

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Appendix D

Information Gathering Meetings and Organizations Consulted

25 & 26 Jan 2000, Washington DC

Air Force Research Laboratory Plans & Programs Directorate (AFRL/XPA)

NASA Langley Research Center

28 Feb 2000 NASA Langley Research Center, Hampton, VA

NASA Langley Research Center

NASA Glenn Research Center

NASA Marshall Space Flight Center

29 Feb 2000, Washington DC

Deputy Chief of Staff for Plans and Programs, Directorate of Strategic Planning, Headquarters US Air Force (HQ USAF / XPX)

Deputy Chief of Staff for Air and Space Operations, Directorate for Command and Control, Headquarters US Air Force (HQ USAF / XOC)

Air Force Historian (HQ USAF/HO)

University of Maryland, Dept. of Aerospace Engineering

Naval Aviation Systems (NAVAIR) 4-4T

28 & 29 March 2000, Washington DC

MIT Lincoln Laboratory

Arnold Engineering Development Center

Princeton University, Dept. of Mechanical and Aerospace Engineering

Defense Advanced Research Projects Agency, Tactical Technology Office

Office of the Deputy Director, Defense Research and Engineering

Director, Force Structure, Resources and Assessment, J-8, the Joint Staff

Johns Hopkins University Applied Physics Laboratory

Office of Naval Research

Air Force Studies and Analysis Agency (AFSAA)

30 March 2000, Boeing, St. Louis, MO

Boeing Phantom Works

18 Apr 2000, Los Angeles, CA

Headquarters Air Force Space Command, Directorate for Requirements HQ AFSPC/DRSV

Air Expeditionary Force Battlelab

NASA Ames Research Center

Kelly Space & Technology, Inc.

19 Apr 2000, Palmdale ,CA & Edwards AFB

Lockheed Martin, Skunk Works

NASA Dryden Flight Research Center

Air Force Flight Test Center Access to Space Office

20 Apr 2000, Los Angeles, CA

Accurate Automation Corp.

Air Force Space and Missile Center, Plans & Programs Directorate, Plans and Analysis Division (SMC/XRD)

MSE Technology Applications, Inc.

Northrop Grumman Air Combat Systems

Orbital Sciences Corporation

Boeing Phantom Works

18 May 2000, Washington DC

Air Force Research Laboratory Plans & Programs Directorate (AFRL/XPA)

Air Force Research Laboratory Propulsion Directorate (AFRL/PR)

Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS)

Air Force Research Laboratory Air Vehicles Directorate (AFRL/VA)

Air Force Research Laboratory Propulsion Directorate (AFRL/MN)

Army Aviation and Missile Command

Headquarters Air Combat Command Directorate of Requirements (HQ ACC/DRM)

National Air Intelligence Center (NAIC/TATV)

Pratt & Whitney

Raytheon

6 Jun 2000, Washington DC

Joint Theater Attack Analysis Center

Deputy Chief of Staff for Plans and Programs, Directorate of Strategic Planning, Headquarters US Air Force (HQ USAF / XPX)

Johns Hopkins University Applied Physics Laboratory

US Army Space and Missile Defense Command

Orbital Sciences Corporation

Headquarters NASA, Office of Aero-Space Technology

General Electric Aircraft Engines

Defense Intelligence Agency (DIA/MS)

University of California Los Angeles, Dept. of Mechanical and Aerospace Engineering

National Air Intelligence Center (NAIC/TATV)

Appendix E

NRC Study Statement of Task Questions and Summary Answers

MEETING OPERATIONAL REQUIREMENTS (2a(i)) Will the Hypersonics Technology Program, as planned by the Air Force Materiel Command (all references to the hypersonics program are directed at this program rather than broader contexts), lead to a capability which will meet operational requirements for hypersonic technology applications?

“Summary Answer: The Air Force HyTech Program, as currently structured, will not lead to an operational capability. Furthermore, the Air Force has not defined operational requirements for the system.

“Recommendations: The Air Force should initiate tradeoff studies for the design and requirements of a hypersonics missile system. Analyses should include the following parameters: targets, speed, range, survivability, lethality, aircraft compatibility, risk, and cost.

“The Air Force should commit appropriate resources to completing integrated airframe-engine flight-testing. Flight tests are vital to demonstrating a hydrocarbon-fueled scramjet in the Mach 4 to Mach 8 regime. If the Air Force decides not to make this commitment, it should re-evaluate its goals for the development of airbreathing hypersonic technology.

“If the Air Force determines that there is a requirement for a hypersonic missile system, then it should establish a system-oriented program office to manage the design and development, integration, and flight-testing of critical enabling technologies for a hypersonic missile system. The program office should report directly to a senior official in a weapon system organization and should have multidisciplinary participation, including experienced design engineers of airbreathing propulsion systems. The committee believes the Air Force must take these steps in the near term for the successful development and application of hypersonic technology by 2015.”

TECHNOLOGIES OTHER THAN PROPULSION (2a(ii)) What technologies (besides propulsion) should next be pursued, and in what priority, for a hypersonic air-to-surface weapon?

“Summary Answer: Several critical enabling technologies besides propulsion will have to be developed for a hypersonic air-to-surface weapon. In order of priority, the five most critical technologies are (1) airframe and engine thermo-structural systems; (2) vehicle integration; (3) stability, guidance and control, navigation, and communications systems; (4) terminal guidance and sensors; and (5) tailored munitions.

“Recommendation: The Air Force should expedite trade-off studies in three separate areas: (1) mission parameters, to establish operational requirements; (2) system concepts, to define candidate configurations with optimum ranges of performance, operability, reliability, and affordability; and (3) technology, to redirect the HyTech projects toward the most promising alternatives, if necessary.”

TECHNICAL COMPONENTS (2b) Are all the necessary technical components of a hypersonic Mach 8 regime propulsion technology program identified and in place, or if not, what is missing?

“Summary Answer: The HyTech program addresses many, but not all, of the propulsion flow path technologies needed to support the development of a Mach 8 missile. The most significant omissions are in the transition to flight, including the development of an operational envelope, a ground-to-flight correlation, and an engine control system. The HyTech Program should also consider a wider range of hypersonic air-breathing propulsion technologies (e.g., uncooled structures and liquid fuel ignition).”

PROPULSION UNCERTAINTIES, (2c(i)) What are the salient uncertainties in the propulsion component of the hypersonic technology program, and are the uncertainties technical, schedule related, or bound by resource limitations as a result of the technical nature of the task (for example, materials sources, qualifications of support personnel, or technology driven costs that affect affordability), to the extent it is possible to enunciate them?

“Summary Answer: The significant technical uncertainties in the overall propulsion system derive from budgetary limitations, are manifested by a lack of focus on risk reduction and on flight demonstration, and cannot be resolved until the current program is completed in 2003. Additional uncertainties exist in the areas of weight, reliability, and affordability. The HyTech Program has not adequately addressed trade-offs at the system concept level between propulsion system capabilities, mission performance, and reliability and affordability.”

OTHER UNCERTAINTIES (2c(ii)) What are the salient uncertainties for the other main technology components of the hypersonic technology program (for example, materials, thermodynamics, etc.)?

“Summary Answer: See the detailed response to the technology uncertainties under 2a(ii).”

TECHNICAL FOUNDATION, (2c(iii)) Does the program provide a sound technical foundation for a weapon system program that could meet operational requirements as presently defined?

“Summary Answer: The current HyTech Program does not have the mandate or the funds to provide a sound technical foundation for a weapons system. The Air Force will have to conduct extensive trade-off studies before it can establish an operational requirement for a hypersonic missile system and determine specific design goals. As a result of concerns that the survivability of this class of missile had not been adequately analyzed, the committee performed an additional study of the survivability trade-offs.”

INTERACTION WITH OTHER PROGRAMS, (2d) How does the Air Force hypersonic program interrelate with other Department of Defense Hypersonic initiatives, for example, the Defense Advanced Research Projects Agency’s Advanced Concept Technology Demonstration on Hypersonic vehicles?

“Summary Answer: The HyTech Program is neither formally coordinated with nor intentionally dependent upon hypersonic initiatives by the US Department of Defense (DoD) or NASA, although relevant technical information is being shared. The committee encourages the Air Force to continue this exchange of information.”

MILESTONE DATES (2e(i)) From an engineering perspective, what are reasonable milestone dates for a hypersonic missile system development program leading up to production, that is, concept development, engineering and manufacturing development,

etc. For example, with a 2015 target date for operational capability, does the current program have a coherent plan and roadmap to build and test a Mach 8 regime hydrocarbon-fueled scramjet engine?

“Summary Answer: The committee finds that initial operational capability for a hydrocarbon-fueled scramjet missile system in 2015 is technically feasible. The committee’s experience indicates that it will take until 2015 to develop the type of missile contemplated by the Air Force with moderate risk. A prototype missile phase will have to be initiated in 2003 and prototype flight testing completed by 2007, which would reduce the risk of entering the engineering and manufacturing development phase. [The] committee’s suggested roadmap...includes a complementary program to the current HyTech Program that will be necessary to reach initial operational capability by 2015.”

A conceptual roadmap, was provided with the detailed answer in the NRC report.

FOREIGN HyperSONIC APPLICATIONS (2e(ii)) Are there foreign hypersonic technology applications that are significantly more developed than those of the United States, that, if acquired by the US government or industry through cooperative venture, license, or sale, could positively affect the development process or schedule for Air Force hypersonic vehicles?

“Summary Answer: Several organizations throughout the world have significant expertise related to scramjet-powered hypersonic vehicles. Although no system-level hardware seems to be available internationally, many technologies of potential use in hypersonic vehicles are being investigated. The committee believes that the Air Force should continue to evaluate potentially significant foreign technologies.”

CONTENT AND PACE OF THE PROGRAM (2e(iii)) Based on these assessments, the committee will make recommendations on the technical content and pace of the program.

“Summary Answer: If the Air Force determines that there is a requirement for a hypersonic missile system, the committee recommends that the Air Force adopt [its] roadmap. To achieve initial operational capability by 2015, the program office recommended in response to Question 2a(i) should establish a roadmap similar to the one developed by the committee. The program should proceed step by step through the various phases, including flight testing, and should address all critical technologies.”

INFRASTRUCTURE (2f) Are there any evident implications for the Air Force support infrastructure for a hypersonic missile system? For example, will other technologies need to be developed in parallel to support a hypersonic vehicle and are those likely to pose significant barriers to eventual success in demonstrating the missile concept or in fielding a viable weapon system by 2015?

“Summary Answer: The implications for the Air Force support infrastructure of a hydrocarbon-fueled hypersonic missile will depend on the maximum speed of the missile. Some investment will be necessary in ground-testing facilities, flight testing, and analyses to determine the performance and operability of the propulsion system. Ground testing facilities will have to support both technology development and demonstration and system development and qualification of a complete missile. Full-scale ground-testing facilities are currently limited to about Mach 7, although modifications to at least one facility are under consideration to support a Mach 8 capability. If a maximum nominal Mach number of 7 or lower is elected, the only modification to a test facility might be to provide for hydrocarbon fuel testing at the NASA 8-Foot High Temperature

Tunnel. Regardless of the maximum Mach number, a capability for the periodic destructive testing of selected missiles from storage must be provided.

“Recommendation: The Air Force should begin planning for the ground-test infrastructure to support the development and qualification of the operability, reliability, durability, and performance of integrated hypersonic propulsion systems over the Mach number range from the speed at the end of the rocket-boost phase to the maximum cruise speed. This infrastructure should be completed expeditiously.”

OVERALL PROGRAM (1) Evaluate and make recommendations regarding the Air Force Hypersonics Technology Program. The NRC should focus its initial efforts on the technologies needed to demonstrate a hypersonic, air-breathing missile concept, using hydrocarbon-based propulsion technology for the Mach 8 regime, in time to achieve an initial operational capability of 2015 or sooner. Emphasize the underlying strategy and key components of the program, the critical technologies that have been identified by the Air Force and by other sources, as appropriate (for example, advanced propulsion systems using ram-jet and scramjet technologies); and the assumptions that underlie technical performance objectives and the operational requirements for hypersonic technology.

“Conclusion: The Air Force’s HyTech Program, which is a Mach 4 to Mach 8 propulsion technology flowpath program, is necessary but not sufficient for the development of a scramjet engine as an integral part of a missile system. Although the limited testing (ground testing only) planned for the propulsion subsystem should indicate its potential engine performance, flight-testing over a representative range of operating conditions will be necessary to determine the engine’s operability, reliability, and durability in an integrated system. These parameters are prerequisites to understanding the engine’s utility in an operational system.

“Recommendation: The Air Force should commit appropriate resources to integrate airframe-engine flight testing, which is vital to demonstrating a hydrocarbon-fueled scramjet in the Mach 4 to Mach 8 range. This recommendation (and the related recommendations that follow) assumes that the Air Force will decide that a hypersonic air-breathing propulsion capability is a potential candidate for fulfilling future system needs (for example, as part of a hypersonic missile or space application). If the Air Force is not willing to commit to flight testing, it should reevaluate its goals for the development of air-breathing hypersonic technology.”

TECHNOLOGY FOR 2015 AND BEYOND (3) to the extent possible, identify technology areas that merit further investigation by the Air Force in the application of hypersonics technology to manned or there unmanned weapon systems by 2015 or beyond.

“Summary: The committee considered possible roles that hypersonic vehicles might play in future Air Force capabilities, particularly global reach and access to space. The committee then identified two program options: (1) the broad pursuit of hypersonic technologies and (2) the evolutionary development of hypersonic technologies based on clearly stated requirements. The committee believes the latter option is the only one that will result in operational systems. On that basis, the committee provided a four-component long-range planning process to guide the Air Force’s development of future hypersonic systems.

“Recommendation: The Air Force should work on the evolutionary development and deployment of systems to meet clearly stated requirements.

“The Air Force should develop a long-range plan incorporating four components as a primary document to guide the development of future hypersonic weapon systems. The four components are operational concepts for future weapon systems and preliminary system designs; scramjet-powered weapons systems using hydrocarbon fuels; hypersonic weapon systems using hydrogen fuel; and combined-cycle system for space access.”

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Appendix F

Plasma Interaction Processes on Hypersonic Vehicles: Electrical Power Generation and an MHD-Scramjet Engine Cycle (AYAKS)

A potentially promising area of investigation for hypersonic vehicles is the use of plasma and magnetohydrodynamic (MHD) processes to achieve a number of improvements in the performance of a hypersonic vehicle and to provide an integrated electrical power source for other applications on the vehicle, such as a DE weapon. It is useful to discuss several of these concepts separately in order to understand the overall potential of this approach.

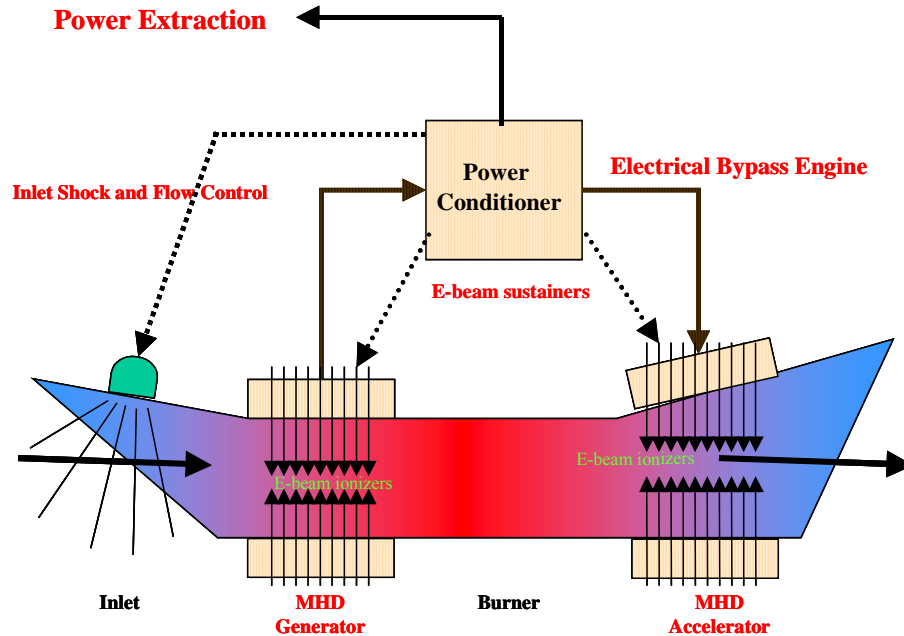
One promising concept is to use a portion of the ionized airflow around a hypersonic vehicle to generate electrical power through the use of an MHD generator. The alternative is to couple the flow from the engine exhaust to the MHD generator. In both concepts, the ionization could be produced in the hot airflow for temperatures in excess of 3,000° Kelvin (K) (corresponding to a speed of Mach 12), could use an external ionization source such as an electron beam, or could seed the airflow with a material that has low-ionization potential, such as cesium.

MHD power generation has been engineered extensively, and the principles are well known. The application to hypersonic vehicles is new, however; the engineering analysis and design trade-offs of this concept require additional work to validate the concept. One can make the following estimates for potential performance: The power per unit area in the gas flow at 0.01 atm pressure, which is representative of a flight altitude of 32 km (100,000 ft), is $P = 0.1 \times M^3 \text{ MW/m}^2$, where M is the Mach number. At Mach 10, there is 100 MW/m² in the free-stream airflow.* If one could optimistically convert 1 percent of this power using an MHD generator, a 10 m² area flow could provide 10 MW_e of electrical power. Assuming a 10 percent conversion efficiency in a DE weapon, one could produce 1 MW of laser power, which is an entry-level weapon. Efficiencies of 1 percent have been demonstrated for ground-based power grid MHD generators. If the practical conversion efficiency is much less than 1 percent, alternative methods for onboard electrical power generation become more attractive. In practice, a 0.1 percent extraction efficiency may be more realistic. A detailed analysis of the MHD power-generation concept is discussed in a later section.

Another concept relates to an increased-performance scramjet, a combined MHD-scramjet engine cycle. This concept is referred to as the MHD energy-bypass or AYAKS concept, a Russian proposal for the engine cycle. The general concept is shown in Figure F-1. The hypersonic airflow is ducted into a channel that contains an MHD generator, then to the scramjet engine, and finally through an MHD accelerator. The purpose of the generator is to extract kinetic energy from the inlet flow in the form of electrical power and to slow down the flow into the scramjet. The bypassed electrical power is used to drive an accelerator section that increases the velocity in the flow and contributes to the overall thrust and I_{sp} to the vehicle. Inherently, this concept will result in a net loss of thrust and I_{sp} in the system, due to system losses in the MHD cycle, unless there are large benefits of increased performance to the main vehicle and scramjet engine, which is claimed to be the case. Some of the electrical power can be used to power other devices on the platform, such as a DE weapon.

* This calculation is equivalent to one that assumes a Mach 10 flight path at constant $q = 0.5\rho U^2 = 0.5 \text{ bar}$.

MHD Power Extraction and Electrical Bypass Engine Concept



Applied Physics Group
Princeton University



Figure F-1. *The MHD Energy-Bypass or AYAKS Concept*

Another concept involves the formation of a plasma in the bow shock, which could result in a significant reduction in vehicle drag. This drag reduction has been demonstrated experimentally on a small scale; however, the physical mechanisms of the process are not well understood. Two different concepts have been considered: a diffuse low-density ionized cloud and a long, slender “plasma aerospoke.” At speeds below Mach 12, the ionization produced by the hypersonic heating of the airflow is insufficient to provide substantial ionization in the bow shock and to provide consequent drag reduction. An independent source is required to produce the required ionization, either in the ionized cloud or in the plasma aerospoke. A number of sources have been proposed for this purpose: DC, radiofrequency, and microwave plasma discharges; laser-produced discharges; and electron and neutron beams. The production of a plasma aerospoke requires a laser or particle beam to produce the required spatial shape of the spike. All of these plasma generators require electrical power, which would be supplied by the MHD generator, or other possible electrical power sources.

Another concept involves vehicle directional control by generating a plasma in a surrounding magnetic field on the front surface of the hypersonic vehicle. Varying the plasma parameters in

the magnetic field can change the direction of the airflow over the vehicle surface, which in turn provides directional control of the vehicle. This concept could present significant advantages over conventional vehicle control surfaces or thrusters in terms of power required and control authority. This concept also requires onboard electrical power to produce and control the plasma in the airflow.

The MHD-Scramjet Engine—AYAKS

The concept is to channel the airflow through an MHD generator, which reduces the velocity of the air stream and produces electrical power. The airflow that exits the generator is introduced into the inlet of the scramjet main engine of a hypersonic vehicle. The exit exhaust is then channeled into an MHD accelerator, which produces a velocity increase in the flow. The enthalpy in the flow is reduced and converted to electrical energy, which is bypassed around the engine and then used to reaccelerate the gas flow in the accelerator section. Typically 20 to 60 percent of the bypass enthalpy is required to get significant increased performance of the scramjet. The intent is to reduce the airflow enthalpy at the engine by reducing the velocity and pressure at the engine inlet. The ideal would be to reduce the velocity at the scramjet inlet to the combustion chamber to a subsonic level, to allow lower temperatures and more efficient operation of the engine as a subsonic ramjet or conventional turbojet.

In practice, the aim is to control the inlet velocity and delay the transition to supersonic flow in the combustion chamber over a wide range of vehicle inlet Mach numbers and flight conditions. This has two apparent effects: (1) the operation of the engine in the ramjet or turbojet mode produces a large I_{sp} and is much more efficient than in the scramjet mode, and (2) there is a significant reduction in drag produced by the engine. It is asserted in some analyses that the major drag experienced by the vehicle is due to internal engine drag itself.

Most of the system analyses for these concepts have been based on a design that originated out of the AYAKS project, which was proposed by a group of Russian scientists beginning in 1990. These concepts were later modeled in greater detail by European and US scientists and were reported in 1997–1998.^{1, 2} These studies also summarize the original references to the AYAKS concept, which describe hypersonic aircraft with operating ranges of 4,800 km to 11,000 km, and some with ranges of 10,000 km to 19,000 km. The speeds are 3.6 km/sec or about Mach 10. All of the proposed concepts have a completely integrated MHD generator-accelerator system to perform the functions discussed above.

A later study of a hypersonic aircraft and lift vehicles was performed by ANSER, Inc. for NASA.³ This study attempted to obtain an estimate of the associated size and weights of a hypersonic vehicle with an integrated MHD generator-accelerator system. To derive the system volume and weight estimates for this study, many simplifying and optimistic assumptions were made, a fact that the authors of the study readily point out. One of the major findings was that the magnets required for the MHD system accounted for 80 percent of the weight in the system. In effect, the study assumed that both the MHD electrical generator and accelerator had nearly perfect conversion efficiency, that is, 50 percent of the energy in the flow could be converted into electricity. In practice, most MHD generators built to date have achieved electrical generation efficiencies of 3 percent or less. Any inefficiencies in the MHD system would greatly increase the weight estimates projected by this study.

The early AYAKS studies projected great performance benefits for an integrated MHD–hypersonic vehicle.^{1, 2} The analyses indicate that the flow enthalpy reduction and operation in the ramjet mode is the major effect. Calculations show that above a velocity of 8,000 ft/sec (2.6 km/sec), the enthalpy bypass and inlet control alone increases the I_{sp} by a factor of 4. There is some decrease in I_{sp} above a velocity of 12,000 ft/sec (4 km/s), but the overall gain in I_{sp} is still a factor of 2 to 3 over that of a scramjet operating at the same velocity. The required enthalpy bypass was in the range of 20 percent to 69 percent. The engine drag reduction increases these gains by an additional 50 percent.

Later analyses of the AYAKS concept predicted a much lower performance increase.^{4, 5, 6, 7, 8} All of these studies were limited to a thermodynamic treatment of the gas flow or a Eulerean treatment of flow variables and shocks, both inviscid (Euler) and viscous (Navier-Stokes) flow. They were essentially limited to conservation of energy and assumed that all of the flow energy could be extracted as electricity with no losses and that the electrical power could be used to accelerate the flow, again with no losses. The analysis presented later will show that the maximum electrical extraction efficiency of the electrical generator is 50 percent of the free-stream energy. This could be an important issue in some of the analyses. The flow was assumed to be adiabatic and isentropic in the inviscid calculations, with a constant ratio for the specific heats. In Reference 4, the increase in I_{sp} ranged from 10 percent to 30 percent for electrical enthalpy bypass fractions of 5 percent to 20 percent. Although ionization of the gas was included, it was treated only in terms of energy loss to ionization and conservation of energy.

The work in Reference 5 included viscous effects to explore inlet diffuser performance for the scramjet. They indicated that an MHD bypass had little effect for inviscid flows but substantial effect when viscous effects were included. In Reference 6, they found that in viscous flow, the introduction of the MHD bypass resulted in an increase in the Mach number in the scramjet inlet, not a decrease as predicted previously. The work in Reference 7 indicates that the performance envelope of ramjet operation can be pushed to higher Mach numbers using MHD enthalpy bypass schemes. They show that the maximum flight Mach number can be increased from Mach 6 to Mach 12 by increasing the bypass enthalpy by 75 percent. Conversely, little performance gain is expected for bypass ratios of less than 40 percent. This is a serious constraint for the MHD bypass scheme.

In the above analyses, there were many optimistic assumptions. There was no realistic treatment of the plasma effects in the MHD generator or accelerator, the ionization processes, the non-equilibrium molecular processes in the gas (such as a constant ratio of specific heats), and realistic engineering details such as magnetic field and electrode design. All of these processes will greatly reduce the performance of the MHD enthalpy bypass concept.

A more realistic analysis of the MHD generator and accelerator systems has been performed by a group at Princeton University.⁹ We will consider this analysis in more detail in order to illustrate the various factors that influence a practical MHD design.

Fundamentals of MHD Electrical Generators and Generator-Accelerator Systems

In this section we consider the basic physics of an MHD electrical generator and accelerator system and the major design factors that govern system efficiency and power extraction. For convenience, we adopted the concept presented and analyzed by the Princeton group.⁹ The

generator accelerator concept is shown in Figure F-1. Note that this system requires a separate propulsion system to maintain the velocity of the vehicle. Otherwise the system shown is a “perpetual propulsion” machine.

The MHD generator produces electricity from the flow of an electrical current traversing a magnetic field (the Faraday effect). This is the same principle involved in a conventional rotating machinery electrical generator. The electrical current is produced by the flow of ionized gas through the channel. The magnetic field needs to be perpendicular to the gas flow to maximize the interaction process. The generated electric field and current flow are perpendicular to both the gas flow and the magnetic field. Electrodes are placed on the sidewall of the channel to extract this electrical power. This configuration is called a Faraday generator. There are also an electric field and current produced along the gas flow, which is called the Hall effect. It is possible to configure electrodes at each end of the flow channel to extract electrical power from the Hall field and current. The Faraday electrodes are short circuited to drive the Hall currents. This configuration is called a Hall generator.

It is essential that the gas flow input to the generator be sufficiently ionized so that the above interactions occur efficiently and deliver significant power. Some ionization can be produced by heating the inlet airstream. However, even at temperatures of 3,000° K the ionization is insufficient to achieve efficient operation of the generator. For comparison, stagnation temperatures for Mach 12 flow are typically 3,000° K, so that this value of Mach number is about the threshold for thermal ionization of air. Conventional MHD generators provide large ionization densities by seeding the inlet gas flow with an easily ionized material such as cesium or potassium. This ionization technique has also been considered for a hypersonic vehicle. The Princeton group has proposed the use of a high-voltage electron beam to provide the required high-ionization density in the MHD channel. This is a technique that has been pioneered and developed in the high-energy laser community for the past two decades. The method is very effective and flexible for producing ionization in the hypersonic gas-flow stream. It is not without its engineering problems, however. One Russian proposal for the AYAKS concept proposes the use of a neutron beam to produce the required ionization density. This method is far less efficient than an electron beam because the neutrons interact much more weakly with the gas than charged particles do.

Following is a brief quantitative analysis of the MHD generator and accelerator which follows the development in Reference 10, further adopting the Princeton configuration shown in Figure F-2. The electric fields and currents generated by the interaction processes are related by a generalized Ohms law of the form

$$j_y = \sigma [(1+b_i b_e) (E_y - UB) + b_e E_x] / [(1 + b_i b_e)^2 + b_e^2]$$

$$j_x = \sigma [(1+b_i b_e) E_x - b_e (E_y - UB)] / [(1 + b_i b_e)^2 + b_e^2]$$

where $b_i = \Omega_i \tau_i$, the Hall parameter for ions, i , and electrons, e . The Hall parameter is expressed in terms of the magnetic gyrofrequency $\Omega_i = e_i B / m_i$ and the momentum collisional decay time τ_i for the ions and electrons. The electrical conductivity is expressed as $\sigma = n_e e^2 \tau_e / m_e$, where n_e is the electron density. Note that the electrical conductivity and Hall parameter are related through the magnetic field, B , and electron density. The above equations are quite general for all electrode configurations and for both the generator and accelerator. These expressions do not

take into account the effects of ion slip, however; we will discuss this effect later. We have assumed that the magnetic and electric fields are spatially uniform in the cross section of the channel, as is the gas flow. Calculations for more realistic geometries and field configurations will reduce the power extraction efficiencies significantly.

We now consider a closely spaced series of segmented electrodes as shown in Figure F-2. In this electrode configuration, the value of j_x is necessarily zero. Combining the two above equations results in a single expression for j_y ,

$$j_y = \sigma (E_y - UB)/(1 + b_l b_e)$$

If the generator electrodes are open circuit, $j_y = 0$, and $E_y = UB$, the maximum electric field that can be produced by the generator. Under short-circuit conditions, $E = 0$. Since the magnitude of the power density generated in the flow is $j_y E_y$, we note that the maximum power output will occur for some intermediate value of the electric field. This is equivalent to impedance matching of the load to the source impedance to promote maximum power transfer.

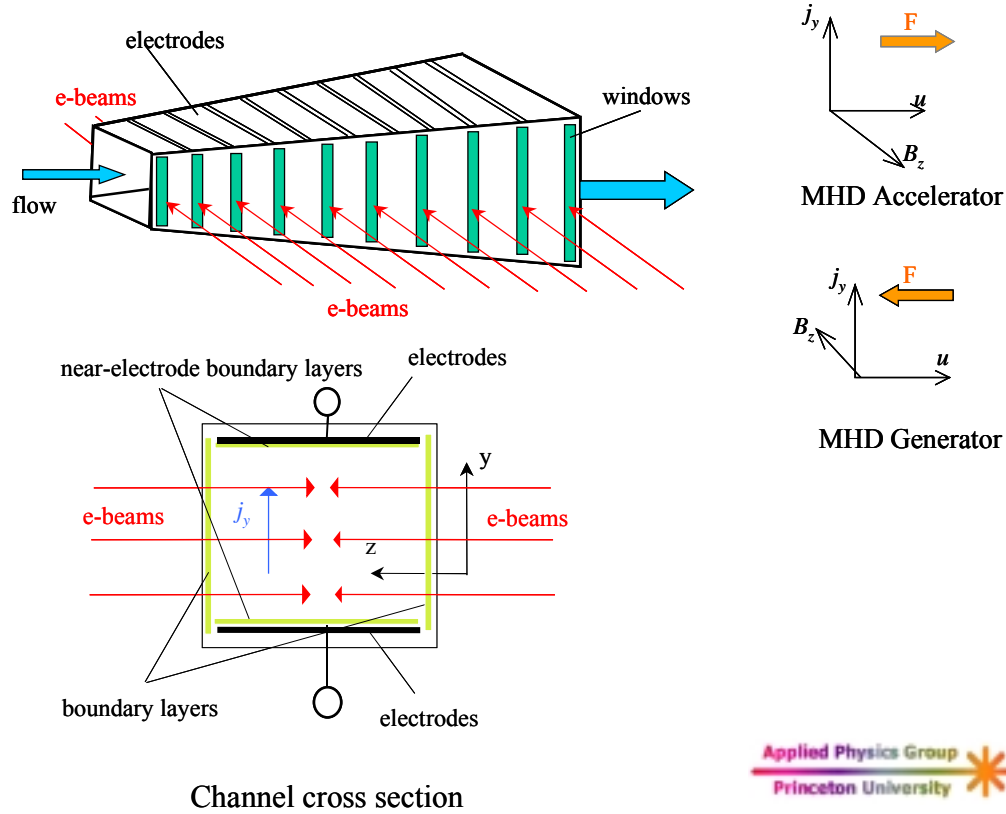


Figure F-2. Geometrical and Electrical Configuration Used for the MHD Analysis

These ideas can be quantified by defining the parameter $K = E/UB$. Since signs are now important, the electrical power density in the flow is given by $P = -E_y j_y$, and the power density can be written in the form

$$P = K(1-K) U^2 B^2 \sigma / (1 + b_l b_e)$$

The power density maximizes for $K = 1/2$, which is a statement of impedance matching. If the Hall parameter b is small for both ions and electrons, the maximum power density that can be extracted from the gas flow is $P = 0.25 \sigma U^2 B^2$. This is the expression used in the ANSER and AYAKS studies.^{1,2,3} As indicated previously, this is a very optimistic estimate for the electrical power extraction. We now consider a more realistic estimate for the power extraction.

A large Hall parameter effectively reduces the conductivity in the gas flow and reduces the electrical power density proportionally. This is expressed quantitatively by

$$\sigma = \sigma_0 / (1 + b_i b_e)$$

The Hall currents tend to oppose the Faraday currents. Ion slip is another deleterious effect not included in the above analysis. Physically, this results from the fact that the local velocity of ions and electrons “slips” behind the average flow velocity of the gas molecules. In the design of MHD generators, the effects of ion slip are also governed by the Hall parameter; consequently the Hall parameter is sometimes referred to as the slip parameter. The effects of ion slip are given by

$$u_i = U / (1 + f^2 b_e b_i)$$

where f is the inverse ionization fraction. No ionization corresponds to $f = 1$ and complete ionization to $f = 0$. Ion slip effects are particularly important for low-ionization fractions. A similar expression applies to the electric current.

If we now use the values of $n_e = 10^{12}/\text{cm}^3$ and $B = 7 \text{ T}$ adopted by the Princeton design, we obtain the value of $\Omega_e = 10^{12}/\text{sec}$. At a reduced gas pressure of 0.04 atm, $1/\tau_e = 4 \times 10^{10}/\text{sec}$. Consequently, the electron Hall parameter $b_e = \Omega_e \tau_e = 25$ and the electrical conductivity $\sigma = 1 \text{ mho/m}$. These values are consistent with those derived by the Princeton group. The value of $b_e b_i$ can be expressed as $b_e b_i = b_e^2 (m_e \tau_i / m_i \tau_e)$. The mobility is defined as $\mu_i = e \tau_i / m_i$ so $b_e b_i = b_e^2 (\mu_i / \mu_e)$. Typically, μ_i / μ_e is 0.1-0.01 so that $b_e b_i$ can achieve values of 5 to 50, with a proportional decrease in conductivity and extracted power. In a weakly ionized gas, the major collisional losses of the ions and electrons are with the neutral gas; the electrons lose a fraction $(m_e / m_i)^{1/2}$ of their energy during a collision while the ions experience a hard-sphere collision and lose almost all of their energy; consequently $\tau_i / \tau_{en} = (m_i / m_e)^{1/2}$. The value of $b_e b_i = b_e^2 (m_e / m_i)^{1/2}$. The value of $(m_i / m_e)^{1/2} = 40 (\text{At})^{1/2}$, where At is the atomic mass of the neutral gas molecules. This simple analysis indicates that there can be a large reduction in the electrical power density that can be extracted from an MHD generator due to Hall currents and ion slip.

The configuration analyzed by the Princeton group included these effects, those of variable flow geometry, and spatial nonuniformities along the flow due to slowing of the gas stream with electrical power extraction. Their results indicate that about 30 percent of the flow power could be extracted in the form of electrical power. In more detail, they assumed $K = 0.447$, a flow velocity of 1,742 m/sec (Mach 4.6), an inlet gas pressure of 0.04 atm, and a duct inlet area of $1/16 \text{ m}^2$. The power per unit area of flow in the neutral gas is $0.5 \rho U^3$ or $6 \times 10^6 \text{ W}$. The extracted power calculated for these conditions is 3 MW, or about 50 percent of the inlet power in the gas flow. Their calculations indicate 35.2 percent power extraction efficiency. The electron beam that is used to produce the ionization requires 178 kW, which is small compared to the flow or the extracted power.

At higher inlet flow velocities of 2,331 m/sec, they obtain 6 MW of electrical power at an extraction efficiency of 26 percent. In these two examples, the inlet flow power has increased by $(2.3/1.7)^3 = 2.4$. The extracted electrical power increased about a factor of 2, which results in a lower extraction efficiency. The value of K was increased to 0.465.

It is useful to discuss the efficiency calculation in more detail. Most of our estimates of efficiency have been defined in terms of the ratio of extracted electrical power to the kinetic power in the gas flow, $q=0.5 \rho U^3$. In fact, one should also include the internal enthalpy in the flow which adds a term of the form $\rho C_p T$, where C_p and T are the specific heat at constant pressure and the gas temperature respectively. When this term is taken into account in the previous calculation, the extraction efficiency is decreased to about 30 percent. This value is now in good agreement with the Princeton group analysis.

In general, in variable area flow with no heat addition, $C_p T + 0.5 U^2$ and $\rho U A$ are constants in the gas flow. The power in the gas flow at any position with area A is just the product of these two expressions or $(C_p T U + 0.5 U^3) \rho A$, which is also a constant as must be the case from conservation of energy. Consequently, we can normalize the extracted electrical power to any position in the flow that is convenient; the free stream inlet, the engine inlet, the engine exhaust, or other. Although a Ramjet or Scramjet does add heat to the air flow, the internal enthalpy is usually smaller than the kinetic terms in the flow, and the velocity increase is small. By normalizing to the kinetic flow energy, one gets an upper bound estimate for the extraction efficiency, which is sufficient for our purposes. Any shock waves in the flow duct or viscous effects will tend to further lower the extraction efficiency.

We now consider other factors that further lower the extraction efficiency. The above analysis assumes that the magnetic is uniform over the whole volume of the gas flow in the channel. However, in a realistic analysis, a larger magnetic field and field volume are required to uniformly fill a given volume of space, due to fringing fields alone. This comment is particularly relevant to the magnetic field configurations considered for the AYAKS concept designs. The construction of a uniform field over a surface of a hypersonic vehicle involves the use of a multipole magnet field configuration. Multipole magnets are notorious for their nonuniformity. While the concept can be made to work, one must allow for the fact that the extraction efficiencies are going to be significantly lower than calculated above. The same comment applies to ionization generation, drag reduction, and vehicle control.

Similar comments apply to the electric field uniformity for segmented electrodes. In this case, the segmentation not only produces electric field nonuniformities, but there are processes in the boundary layer in the flow next to the electrodes that can cause arcing, electrode erosion, and other deleterious effects due to the large Hall parameter in the boundary layer. There is also significant heating near the walls, which further complicates the boundary layer effects.

One important effect is the enthalpy loss in the kinetic flow energy due to vibrational excitation of the nitrogen in the air—that is, a reduced value of the specific heat ratio, γ . The electric field produced in the Princeton analysis is $KUB = 6,000 \text{ V/m} = 60 \text{ V/cm}$ at a gas pressure of 0.04 atm. These values translate to an $E/p = 1.5 \text{ kV/cm-atm} = 2 \text{ V/cm-torr}$. These values are too low to produce significant ionization in the gas, but are almost optimum for producing significant vibrational excitation in the gas. This is an effect that is used in high-power carbon-dioxide lasers to optimize vibrational excitation. Both calculations and experiments show that under

these excitation conditions, almost 90 percent of the electrical energy input is converted into vibrational excitation of the nitrogen. The vibrational energy becomes “frozen” in the flow and is unavailable for electrical power extraction. This frozen flow effect is used in the high-power carbon-dioxide dynamic lasers. The vibrational effects were recognized by the Princeton group and included in their analysis.

System Analysis Guidelines for Evaluating MHD Concepts for Hypersonic Vehicles

Taking into account all the above efficiency factors could yield estimates of a realistic electrical power extraction for MHD generators. However, this requires a level of analysis beyond the scope of this work. Instead, we resort to the literature on experimental demonstrations of MHD power generation. This was a very active field in the 1960s and 1970s. The best extraction efficiency that was produced under optimized conditions was 3 percent for a 600-kW generator (AVCO-Mark III). The largest generator built was the AVCO-Mark VI, which produced 11 MW at a 1 percent extraction efficiency. At 10 MW and larger power levels, it would seem reasonable that a realistic MHD generator efficiency could be 1 percent, with a design goal of 10 percent.

A typical overall generator-accelerator efficiency may then be 0.0001 or 0.01 percent. Any external power extraction would reduce these values further. Any system analysis of MHD concepts for hypersonic vehicles should use the above values to determine the utility of the concept. Electrical power extraction for external use on the hypersonic vehicle should be scoped for a maximum extraction efficiency of 1 percent, with a future goal of 10 percent. It may be that clever methods to connect the generator and accelerator will result in a much improved performance.

As we will show, most of the above analysis and comments also apply to MHD accelerators. To reiterate, the current generated in an MHD device is expressed as

$$j_y = \sigma (E_y - UB)/(1 + b_l b_e)$$

The vector force on an elemental volume of ionized material is given by $F = j \times B$. The fact that the magnetic field is along the z axis and that the perpendicular current is primarily due to electrons in the above analysis gives a volume force along the flow direction of

$$F = \sigma B (E_y - UB)/(1 + b_l b_e)$$

If $E/UB = K < 1$, the force is directed opposite to the flow velocity. This slows the gas flow, and this energy loss in the flow appears as electrical power. If $K > 1$, the force is positive and along the flow. In this case, the flow is accelerated. All of the analysis for the MHD electrical generator then applies to the MHD accelerator, except that $K > 1$.

It is useful to define a force coefficient, $C = F/0.5 \rho U^2$, which is the ratio of the MHD force to the pressure exerted by the neutral gas flow. If we now define the dimensionless parameter Q^* as

$$Q^* = \sigma B^2 L / \rho U,$$

we can write the force equation in the form

$$F L = (K-1) Q^* 0.5 \rho U^2 / (1 + b_l b_e)$$

where F/L is the force per unit area exerted on the flowing gas and L is the length of the flow channel. If we now define the quantity $C/L = F/L/0.5 \rho U^2$, the statement that $C/L = 1$ is one of exact pressure balance between the MHD forces and the gas flow. This constraint then requires that $|K-1| Q^*/(1 + b_I b_e) < 1$. For the generator, $K = 1/2$ for maximum power extraction. Q^* is then limited to values such that $Q^* < 2(1 + b_I b_e)$.

The maximum power extraction per unit area of duct for the MHD generator averaged over a length L is then given by

$$P/L = K(1-K) Q^* 0.5 \rho U^3 / (1 + b_I b_e) < K(0.5 \rho U^3)$$

This is now the maximum power that can be extracted from the flow. For $K = 1/2$, the maximum efficiency is 50 percent. This is because extraction efficiency decreases over the flow length as the flow is slowed. The flow at the end cannot be reduced to zero. For 50 percent extraction efficiency, the flow velocity is reduced by $2^{1/2}$ at the exit.

In the generator, $K > 1$ so that the power delivered to the flow field is only

$$P/L = K(1-K) Q^* 0.5 \rho U^3 / (1 + b_I b_e)$$

But now the constraint is $|K-1| Q^*/(1 + b_I b_e) = 1$ so that Q^* is less for the generator than the accelerator since $K > 1$. In principle, the flow can be accelerated to any velocity with 100 percent conversion efficiency.

Relation Between Ionization and Magnetic Field

Although it would appear in the earlier analysis of the power extraction in an MHD generator that the ionization fraction, magnetic field, flow velocity, and duct length are independent variables, the constraint on Q derived from the conservation of energy couples all of these parameters. The expression for Q can be rewritten in terms of the ionization fraction α as

$$Q^* = \alpha b_I b_e \tau_{\text{tran}} / \tau_I (1 + f^2 b_I b_e)$$

where $\tau_{\text{tran}} = L/U_I$ is the transit time of an ion through the channel length L . We have used the relation that $U_I = U/(1 + f^2 b_I b_e)$. For large Hall parameters, the constraint on Q fixes L by the relation that $\tau_{\text{tran}}/\tau_I = 1$, which is a statement that at least one ion collision must occur in an ion transit time through a length L of the MHD channel.

The constraint on Q was derived above by conservation of energy and pressure balance. In fact, the plasma physics forces a constraint on Q that occurs at large power extractions from the gas flow. These limiting processes involve the increased ion slip as indicated in the above expression for Q^* as a function of the inverse ionization fraction $f = (1-\alpha)$.

Findings and Recommendations

The use of various plasma processes to reduce drag on supersonic and hypersonic vehicles appears to be very attractive and should be pursued with a high priority by the Air Force. The use of plasmas to provide flight control of a hypersonic vehicle also appears to have great potential, as does the use of MHD concepts on hypersonic vehicles to reduce drag and optimize ramjet and scramjet performance. It should be noted, however, that most of this increased

performance accrues due to the resulting inlet velocity and pressure control on the scramjet engine. The analyses to date of this particular effect are too crude to evaluate the real potential of the concept. All of the modeling tools, however, have been developed to evaluate nonequilibrium and plasma processes in the MHD system, as well as the engineering issues for the MHD generator and accelerator. Until these performance analyses have been carried out, it is premature to speculate on any enhancements in the performance of the scramjet/ramjet hypersonic aircraft. The same is true for the MHD electrical generation concept.

An alternative is to generate the electricity from an onboard lox-hydrogen turbo alternator. This technology is compact, and it is ready today for power sources at the 10-MW level. Hypersonic vehicles with speeds in excess of Mach 8 must carry hydrogen fuel. Small amounts of this fuel could then be used to power the lox-hydrogen turboalternator. Any system analysis of these power-generation concepts should present a performance and weight comparison between MHD and lox-hydrogen turboalternators.

Future work should focus on detailed and realistic modeling of MHD generators and accelerators on hypersonic vehicles particularly the basic processes and the engineering design. The Princeton group analysis appears to be the most detailed and realistic to date. However, much remains to be done in determining the limitations on electrical power output and extraction efficiency for MHD devices. A strong experimental program should be coupled to this modeling effort in order to validate the understanding of the mechanisms basic to MHD devices in hypersonic flows. No vehicle demonstration program is warranted until this modeling and experimental program is complete. A similar program is needed involving the plasma concepts developed for drag reduction and vehicle flight control.

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Appendix G

Physical Considerations for Hard-Target Penetrators

Background

The science and measurement of penetration of materials by long-rod penetrators has been studied for many years. It has major applications in the areas of armor penetration and deep earth penetrators. The interaction physics is different in these two applications, and it depends strongly on the velocity of the penetrator. The momentum and kinetic energy of a cylindrical rod traveling at a velocity V with a mass M at impact is given by $I = MV$ and $KE = MV^2/2$ respectively. A steel penetrator with a mass of 300 kg (660 lb) moving at 1.2 km/sec (4,000 ft/sec) has a kinetic energy of 216 MJ, or an energy equivalent of approximately 50 kg (100 lb) of high explosive. An explosion of this magnitude produces a hole about 1 m deep in loose soil. The large penetration depths produced by a rod penetrator result from the fact that a large force per unit area or pressure is produced at impact, and this pressure persists for a long period compared to the detonation of high explosives.

The kinetic energy per unit area of the penetrator is roughly given by mV^2 , where m is the mass per unit area or areal density; for a rod, this is given by $m = \rho_p L$, where ρ_p is the density of the penetrator. Since the area of the penetrator is $\pi D^2/4$ and the mass is $M = \rho_p L \times \text{area}$, we can write kinetic energy per unit area as $M/A \times V^2/2$. The first term has the units of pressure, and the second is just the kinetic energy per unit mass or the specific kinetic energy. The penetration depth in a target should increase as some function of these two terms—up to a point.

The pressure induced in the penetrator at impact is just $\rho_p V^2$. When this value is comparable to the yield stress of the penetrator material, the penetrator loses its mechanical strength, and the material bends, breaks, or melts, depending on the value of specific kinetic energy. An additional strength parameter of the penetrator is governed by the ratio of length-to-diameter (L/D). In first approximation, the bending of a rod due to the loading force produced by the deceleration of a penetrator in a target W is related by $W \propto (L/D)^{-2}$.

The above relations can be stated more concisely. If the yield or flow stress of the material is Y , then the ratio $\alpha = Y/\rho V^2$ determines the physics interaction regime for both the penetrator and the target. When $\alpha \cong 1$, the material has lost most of its strength. If $\alpha \cong 0.1$, the material is essentially a fluid and is now in a hydrodynamic regime. On the other extreme, if $\alpha \cong 10$, the material can be considered a true solid, and the mechanical properties of the material dominate the interactions.

The regimes in which α is very large or very small can be calculated with simple theory, and the predictions agree well with experiments. The regime in which $0.1 < \alpha < 10$ is a very difficult regime in which to formulate a physical model and perform experiments, and it is under active investigation.

Range of Interest

We now calculate the value of α for a steel penetrator and various target materials. The value of the yield strength is nominally 170,000 psi = 1.16×10^9 Pa. The density is 7,900 kg/m³. In

Table G-1, we calculate the value of α for several different impact speeds. We also calculate α for targets of granite ($Y = 450,000$ psi) and 5,000-psi concrete. The density of concrete is $2,400 \text{ kg/m}^3$ and the density of granite is $2,700 \text{ kg/m}^3$.

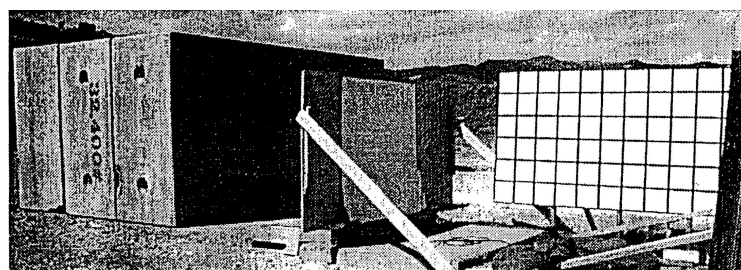
Table G-1. Value of α for Various Materials and Impact Speeds

Velocity (ft/sec)	Velocity (m/sec)	α (steel)	α (concrete)	α (granite)
3,000	900	0.18	0.018	0.14
4,000	1,200	0.1	0.01	0.074
5,000	1,500	0.06	0.006	0.046
6,000	1,800	0.045	0.0045	0.035

The numbers in Table G-1 indicate that a steel penetrator begins losing its strength at about 4,000 ft/sec (1,200 m/sec). At 6,000 ft/sec, one would expect that the penetrator would have very little mechanical strength left and that the penetration would approach that of a fluid jet, much like a shaped-charge penetrator. A second observation is that granite looks mostly like steel in this velocity range, and the above observations apply also to a granite target. In concrete, the onset of the hydrodynamic regime appears to occur even at the lowest velocity in Table G-1. In the low-velocity regime, the interaction is like a solid-steel rod penetrating a target of putty. In the higher-velocity regime, the penetration interaction is similar to the impact of putty on putty, which is very complicated. At higher velocities, the interaction can be treated using the simple conservation laws of fluid dynamics.

The above limits set by α are approximate, but should not vary by much over a factor of 2, and consequently the velocity by $2^{1/2}$. The penetration depth also depends on the value of L/D and on the angle of the penetrator normal at impact with respect to the target. The major conclusion is that for impacts of steel penetrators in granite and concrete, the maximum penetration depths will occur for a velocity that is nominally 4,000 ft/sec. These numbers are in good agreement with experimental results obtained under controlled conditions with small-diameter penetrators in 5,000-psi concrete at Sandia National Laboratory. Researchers were able to achieve 4,500 ft/sec at a penetration depth of 12 ft with a 30-lb penetrator that had an $L/D \approx 8$ ($L = 24$ inches and $D = 3.3$ inches). However, if the off-normal impact angle was larger than 1° , the penetrator apparently bent and the velocity vector shifted almost 90° within the target. A summary of these data is shown in Figures G-1 and G-2.¹

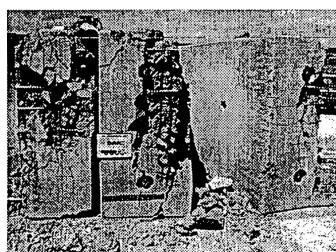
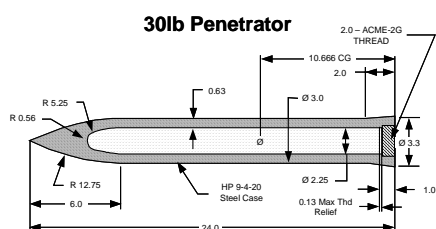
Damage to Concrete Target Due to 30 lb Kinetic Energy Penetrator



Test setup showing 3 16-ton concrete blocks and calibrated screen for measuring exit velocity.

BEFORE

AFTER



Concrete blocks after 30 lb. projectile has passed from left-to-right. Note how blocks have been physically translated (they were in direct contact) and spalling has occurred. Note entry hole in block on right side.

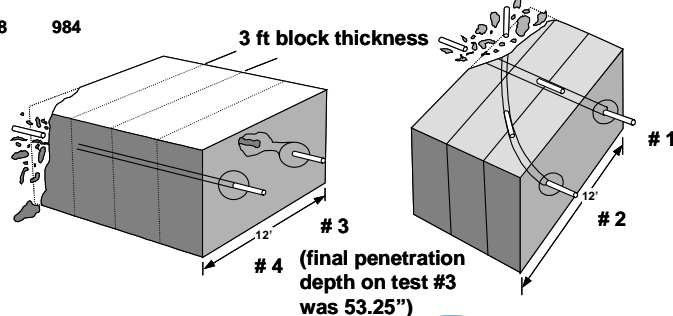
Sandia National Laboratories

Figure G-1. Damage to a Concrete Target From a 30-lb Kinetic Energy Penetrator

Summary of New Mexico Tests of 30 lb. Penetrator into Concrete Targets

Test No.	AOA	Slab Thickness	V_{in}	V_{extl}
	(deg)	(ft)	(ft/sec)	(ft/sec)
1	1	9	3680	1524
2	1.5	9	4470	?
3	1	12	4507	0
4	0.5	12	4058	984

Concrete, $\frac{3}{4}$ " aggregate, 5000 psi ave. 28 day strength. Reinforced with #6 rebar on 8" center



Sandia National Laboratories

Figure G-2. Test Results From Driving a 30-lb Steel Penetrator Into Concrete Targets

Other less well-diagnosed experiments by Orbital Sciences Corporation that were presented to the SAB committee indicated that they could deliver a 300-kg (660-lb) penetrator with an impact velocity of 4,000 ft/sec into an earth granite target. The measured depth of penetration was 45 ft. The penetrator that was recovered after the experiment indicated little erosion and loss of mechanical strength, although the penetrator did appear to be slightly bent. The length of the penetrator was 5 ft and the diameter was 9 inches, which gives $L/D = 6.6$. The areal mass $M/A = 10.4$ psi. In another experiment, a 4-ft-long, 256-lb steel penetrator impacted granite at a velocity of 3,300 ft/sec. The penetration depth was 31 ft in granite. The diameter of the penetrator was 6 inches, which gives $L/D = 8$ and an $M/A = 9$ psi. The penetrator in these tests was a solid body with no interior space for a warhead. In a practical device, such space would be required, which would weaken the mechanical strength of the penetrator and reduce the penetration depth.

As a final example for comparison, we consider the deep penetrator gravity bomb, the GBU-28. The device is 153 inches (12.75 ft) long and 16 inches in diameter, and it weighs 5,000 lb. The impact velocity is 1,350 ft/sec (405 m/sec). The relevant values for this penetrator are $L/D = 9.6$ and $M/A = 24.8$ psi. The impact velocity is very low compared to the values considered above for high-speed impactors.

A summary of the above data and a comparison with calculations are presented in Figure G-3. As indicated, the desired result is a high M/A and a velocity that is as high as possible, up to about 4,500 ft/sec. At this point, the penetrator loses mechanical strength or bends. A value of $L/D = 9$ is about the maximum of the penetrator length to diameter ratio that can be achieved without bending. Above a velocity of 4,500 ft/sec, the penetrator seems to rapidly lose mechanical strength.* It is an open question whether the penetration depth is maximum at this velocity. All of the above considerations indicate that the penetration depth would not increase substantially above this velocity; in fact, it must decrease in the hydrodynamic regime, where analysis indicates that the ratio of penetration depth to penetrator length is approximately equal to the ratio of the square root of the densities in the penetrator and the target. For steel and granite, this ratio is only 1.7.

* These curves are based on an empirical expression for the penetration depth developed by C. W. Young at Sandia National Laboratory. The author cautions that the use of these functional expressions should be limited to projectile velocities of less than 3,500 ft/sec for the reasons presented in the text.

Velocity & Weight/Area Ratio are Important Parameters for Penetration

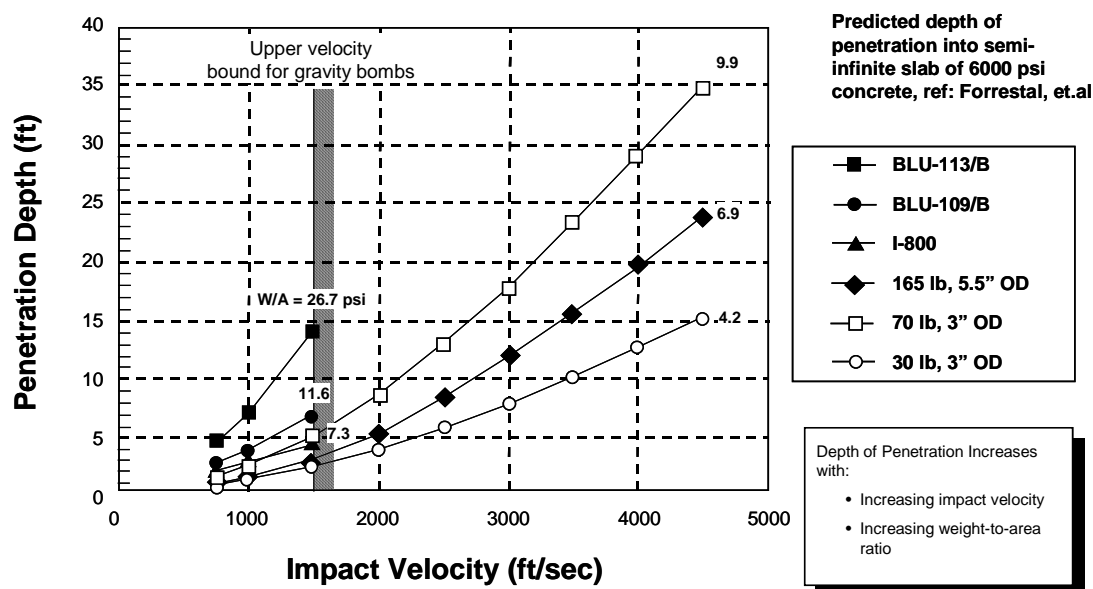


Figure G-3. The Effect of Velocity and Weight/Area Ratio on Penetration

Figure G-4 and Figure G-5 further clarify the above analysis.² An impact velocity of 5,000 ft/sec lies in the middle of the diagram in Figure G-4, indicating the brittle or ductile regime of the penetrator material. The matrix shown in Figure G-5 indicates the basic interaction physics regimes in terms of the parameter $\alpha = \sigma/P$ (note the inverse definition of alpha used in the table) for both the penetrator and the target. Note that earth penetrators operate in the (1,3) region whereas hypersonic impacts on concrete occur in the (3,1) region. The impact of a 4,000 ft/sec penetrator with a granite target occurs in the (2 and 3) region of the chart.

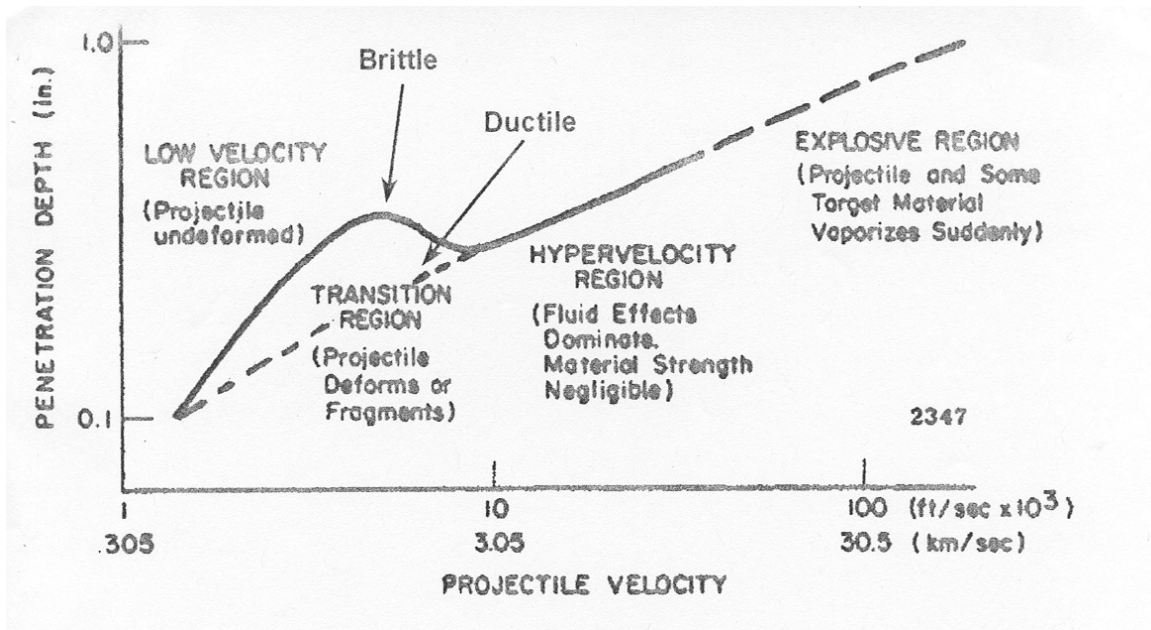


Figure G-4. *Notional Plot of the Penetrator Performance and Mechanical Properties as a Function of Impact Velocity*

Findings and Conclusions

Both experiments and the basic physics of hypersonic penetrator interactions with targets indicate that the maximum useful impact velocity is about 4,500 to 5,000 ft/sec for steel penetrators. Larger velocities will result in a loss of mechanical strength, bending of the penetrator, and decreased penetration depth. The penetration depth depends on the value of the mass-to-area ratio, M/A , of the penetrator and L/D . For experiments to date, $M/A < 25$ psi and $L/D < 10$. All penetrator experiments, calculations, and data are consistent with these findings. However, it is important to continue well-controlled experiments to determine the maximum useful velocity to maximize the penetration depth in various targets.

All of the above limits assume normal impact on the surface of the target and a homogenous material in the target. Any inhomogeneities in the target—such as large rock aggregate, large voids, and layered or angled slabs—would tend to exacerbate the bending or deflection of the penetrator and would reduce the penetration depth. The same effect may occur with an overburden of loose soil on the target. The off-angle impacts on the target must be less than 1° to 2° , or the penetrator will bend and the penetration depth will be reduced. Attacks on unknown targets may be more effective with penetrators of lower than maximum velocity, which would alleviate the off-normal impact requirement and inhomogeneous effects of the targets. Further analysis and trade-off studies are required in this important area.

Benefits of a Hypersonic Penetrator

Comparison of the weights of a large gravity bomb and an equivalent hypersonic penetrator indicate that the penetrator can be reduced from 5,000 to 250 lb to get a comparable penetration depth. Since the penetration depth is proportional to $M/A \times V^2/2$, a reduction of 20 times in

mass can be traded for a $20^{1/2}$ increase in velocity. For the GBU-28, the impact velocity is 1,300 ft/sec. Using the above scaling, the velocity must be increased to 5,800 ft/sec. In practice, the velocity scaling is more favorable, and the scaled velocity is only about 3,000 ft/sec. This could be an important advantage for use with hypersonic strike aircraft or UAVs.

A booster motor on a hypersonic penetrator could provide precision control on the point of impact and angle of impact of the penetrator. These are both important parameters in maximizing the penetration depth of the weapon.

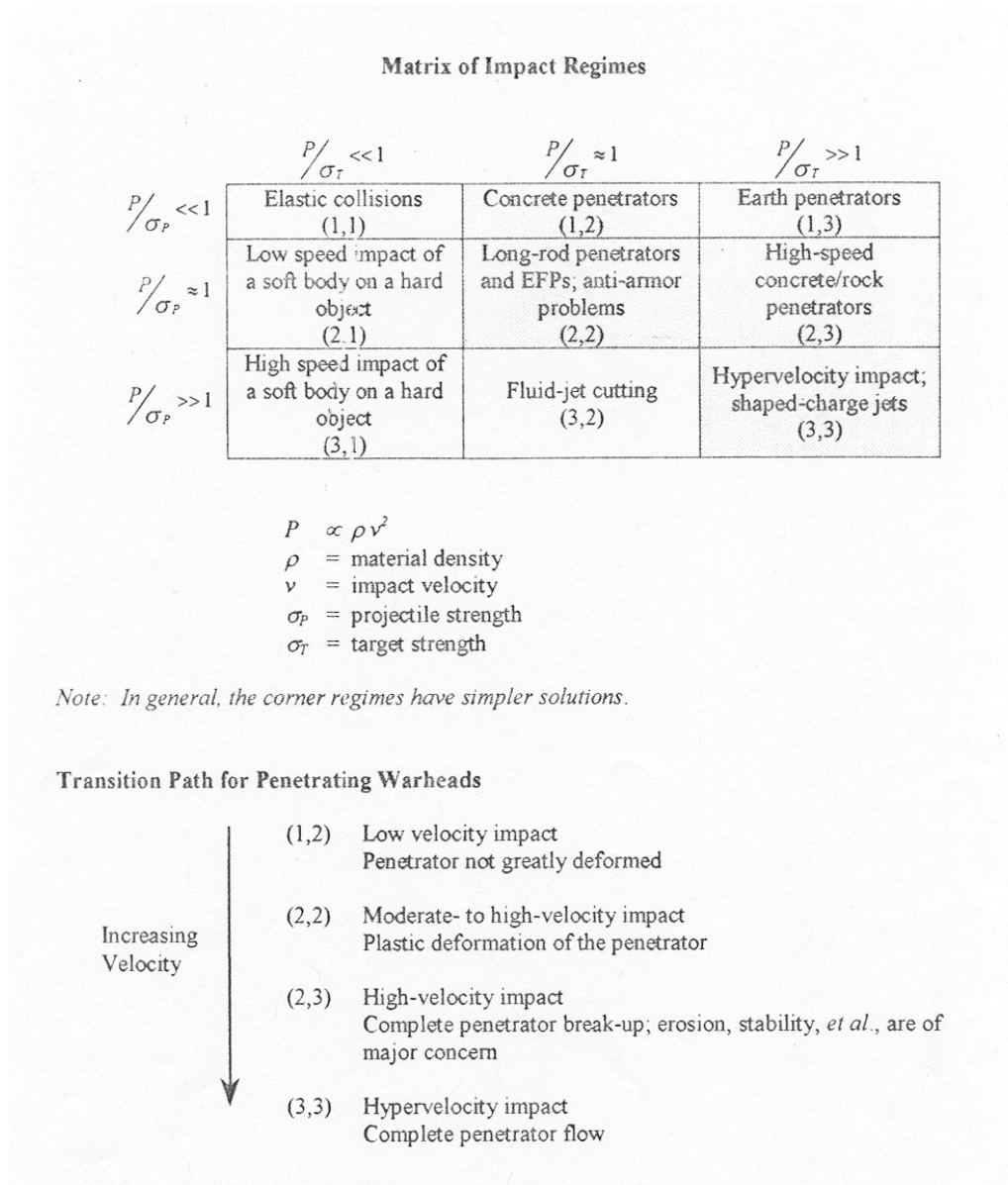


Figure G-5. Matrix Diagram Indicating the Important Mechanical Properties in Both the Penetrator and Target at Different Impact Velocities and Internal Pressures

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Appendix H

Why and Whither Hypersonics Research in the US Air Force Briefing

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Why & Whither Hypersonics Research in the USAF



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Preview

- **The USAF already has some important hypersonic systems**
- **For the Air Force Vision of “controlling and exploiting the full aerospace continuum” to become reality, the USAF should focus on space and transatmospheric operations**
 - Clear statements of military mission requirements are needed
 - If responsive launch to flexible space orbits and maneuvering flight at sub-orbital altitudes are required
 - USAF needs to transition from expendable to reusable launch vehicles
 - Rocket or air breathing hypersonic alternatives are viable
 - The jury is out on the “best” alternative
 - Conversely, if responsive launch to flexible space orbits and maneuvering flight at sub-orbital altitudes are not required, the Air Force can probably live with expendable launch vehicles
 - Air breathing hypersonics could provide the capability with some interesting spin-offs:
 - Access for global attack enabling defeat of enemy anti-access strategies
 - Inherent aerospace superiority with directed energy precision engagement
- **There is a great opportunity to leverage NASA's investment**
- **It's time to make the Vision a reality**

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Terms of Reference

- Build on the National Research Council (NRC) hypersonics report
- Review the Air Force Research Laboratory (AFRL) roadmap
- Develop operational concepts in both narrative and strategy-to-tasks formats that require hypersonics speeds (including sustained hypersonic speeds) to enable/underwrite air force capabilities to achieve operational objectives
 - Consider the multi-week planning cycles at National Command Authority (NCA) level and explain why conventional platforms can't perform the national security mission given days and days-to-weeks of truce-to-preposition
- Recommend a time-phased investment plan based on operational need and technology availability. This plan will identify key S&T investments, exit criteria, demonstrations necessary for transition to EMD decisions, and considerations for speeds beyond mach 8
- Form a red team to argue the proposition that hypersonic has no military utility, or at least none given costs and available work-arounds

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3



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Study Team

Ron Fuchs (Chair)
BG Dave Deptula (GO Participant)
Maj Doug Amon (Exec)

Ops Concepts	Red Team	Investment Program
Dave Frost (Chair)	Tom McMahan (Chair)	Armand Chaput (Chair)
Dave Vesely	Darryl Greenwood	Ray Chase
Buck Buchanan	Al Bernard	Fred Billig
Natalie Crawford	John Jaquish	Ray Johnson
Tom Cruse	Dean Judd	Ann Karagozian
Dick Hallion	Howard Schue	Sherm Mullin
George Orton	Mike Yarymovych	Jason Speyer
Capt Matt Murdough	Capt David Jablonski	David Van Wie
		Vince Rausch
		LtCol Dan Heale
		Capt Sue Hastings

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4



The Many Faces of Hypersonics

For this study's purpose we simply define "hypersonic" as $>\text{Mach } 5$, (or about 1 mile/sec)

The AF has been in the hypersonic business for over 40 years. This study focuses on air-breathing hypersonic systems.



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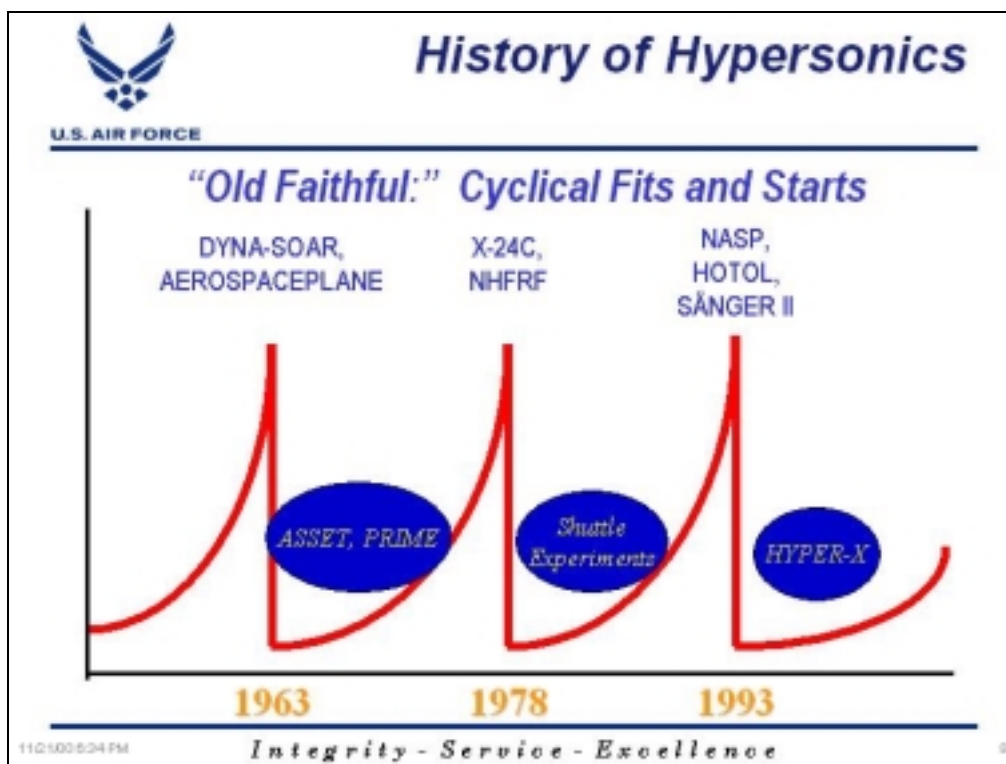
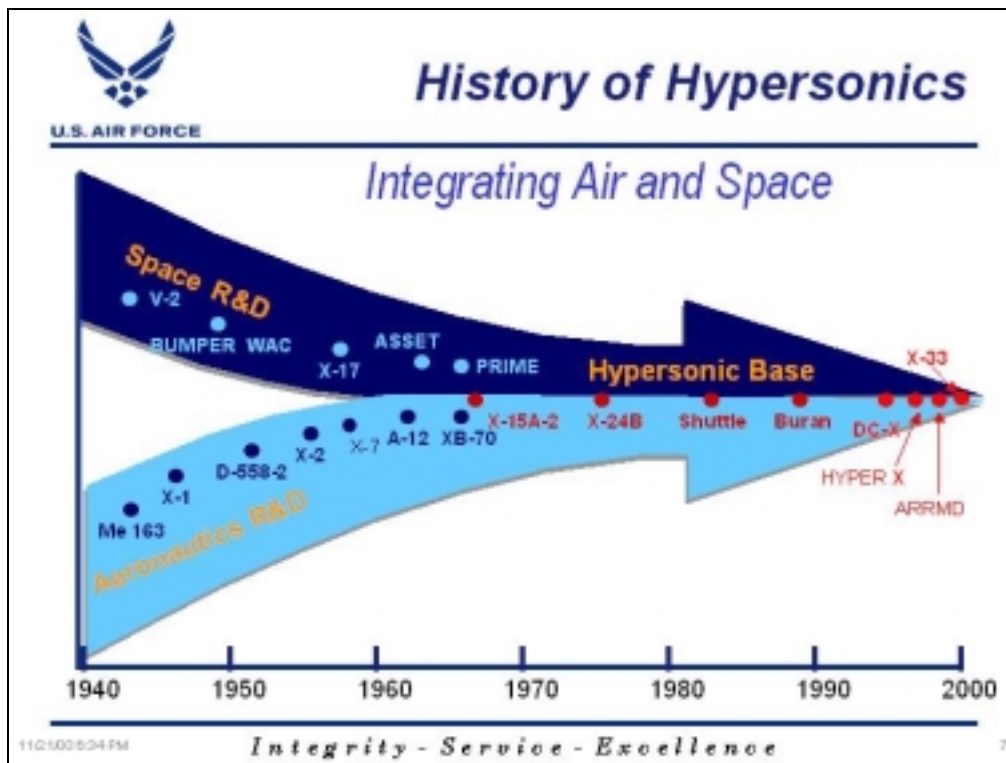


Background Information




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History of Hypersonics

"History May Not Repeat, but it Sure Does Rhyme"

HYPERSONICS IS AT THE SAME CROSSROADS
SUPERSONICS WAS FIFTY YEARS AGO

- Inadequate Federal organizational structure
- Serious ground test facility shortfalls
- Inherent risk and design uncertainties
- Subscale substitutes: weighted bodies then, AARMD now
- Controversial Tech Demonstrators: X-1 then, Hyper-X now
- Disadvantageous economic (Defense spending) conditions
- NO OBVIOUS OPERATIONAL REQUIREMENT

*But would a reasonable person today say we made a mistake
supporting supersonic research and development????*

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Rules of Thumb

- Hydrocarbon fuels allow air breather speeds to ~ Mach 8; liquid hydrogen allows higher speeds
- Two stage to orbit is a more feasible hypersonic approach than Single Stage to Orbit (SSTO)
- Hypersonic speed makes a vehicle more survivable, but is not adequate without other aids (signature, maneuvering, etc.)
- A few deeply buried targets are not vulnerable to kinetic energy alone
- Unassisted power extraction from flow begins ~ Mach 10
- Other general hypersonic info:
 - Considerable R&D is yet required prior to fielding
 - 15 years to hypersonic weapons
 - 20 years to a hypersonic aircraft or RLV
 - NASA is not developing to military requirements

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Ongoing Efforts in Hypersonics

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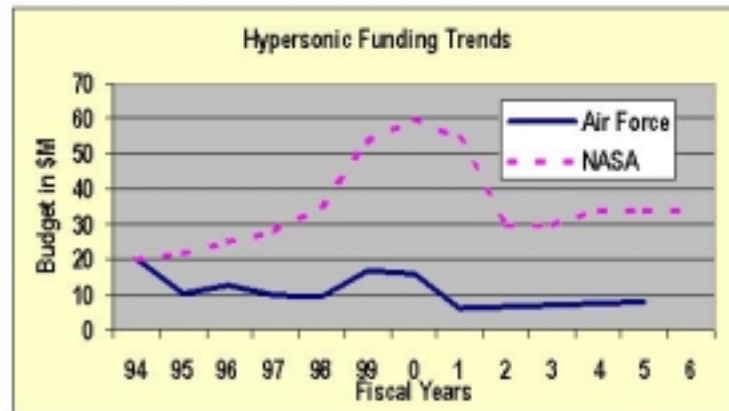


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US Air Breathing Hypersonics Technology Roadmap



Air Breathing Hypersonics Funding



**NASA funding is reasonably robust for a technology effort –
Air Force's is inadequate to significantly influence the
overall program**

Foreign Hypersonic Activities

- **Space Access Threat:** Breakthrough launch technology will allow ready access to the space environment
 - Russia: ORYL Program – developing engine/airframe technologies, significant existing infrastructure, flight tests conducted
 - Japan: On-going long-term investment in space access propulsion technologies, significant facilities investment
 - France/Russia: Developing Wide Range Ramjet
 - ESA/Germany: Paper assessments on-going
- **Weapons Threat:** Hypersonic cruise missile development represents an asymmetric attack on force structure
 - Russia: Operational supersonic air breathing missile, hypersonic cruise missile technologies highly evolved
 - China/India: Operational supersonic ramjet missiles, new entries to hypersonic field, rapidly playing catch-up
 - France: Operational supersonic air breathing missile, investing in hypersonic missile technologies
- **Fundamental Technology Threat:** Radical technology breakthrough may fundamentally change hypersonic vehicles
 - Russia: Significant investment in plasma/MHD aerodynamics, plasma cloaking

Significant foreign activities are underway in hypersonics

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Potential Air Breathing Hypersonic Applications

Weapons (missiles)

- Time Critical Mobile targets
- Hard and Deeply Buried Targets
- Reactive Lethal SEAD
- Counter Air
- BMD/TBMD



Aircraft

- Global Strike/Recce
- Survivable DEW/ABL Platform
- Rapid resupply



Space Operations

- Routine launch
- Replace & maintain key satellites
- Protect US/Coalition satellites
 - Anti-ASAT
- Deny hostile/non-combatants use of space
 - ASAT
 - Satellite capture/disable

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Space Operations

■ Current AF Aerospace Vision

- Control space when need be
- Capitalize on space advantages
- Engage anything of military significance anywhere
- Engage within minutes, not hours
- Achieve desired effects from any chosen range
- Strike from CONUS
- Improve stand-off capability

■ Current Realities

- AF does not have a capability for access, operations, or dominance in the transatmosphere today
- AF can not engage anywhere within minutes except by ICBMs
- Space sortie rate will be cost limited using EELVs
- Stand-off capability improved by Hypersonic missile

The reality does not match the Vision

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Airbreathing Reusable Launch Vehicles (RLVs)

Some Options



Mach 4-5 Air breathing 1st stage



Mach 8-10 Air breathing 1st stage



Mach 23 Air breathing 1st stage

Airbreathing reusable launch vehicles could satisfy long term (2025) requirements for Air Force, NASA, and Industry

- Low enough costs and responsiveness to satisfy future Air Force launch needs (e.g. SMV, SBR and SBL) and create commercial markets
- Robustness and safety necessary to allow safe human operations in space

Airbreathing stages of RLV can serve dual role: space missions and prompt global attack from CONUS

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Assured Space Access: Alternatives

Baseline Concept



PRO

- Enables Air Force transatmospheric and space operations
- Potential for significant cost reduction
- Fast turnaround enabled/required (aircraft-like ops)
- Potential spin-offs

CON

- Cost reduction might not be realized (eg. Shuttle)
- Large launch rate to amortize cost may not be realized
- Large technology investment risk (~\$1B)
- High program cost (~\$25B)

Rocket-powered RLV



- Potential for cost reduction, but less than airbreathing
- Payload recovery

- Cost reduction might not be realized
- Program cost ~\$15B (though lower cost than air breathing)
- Turnaround not as fast as air breathing
- Possibly fewer launch and retrieval options

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Assured Space Access: Alternatives

EELV



PRO

- Extension of current ELV technology
- Affordable
- Well established ops concept

CON

- Dead end to cost reduction below about \$2500/lb to orbit
- Cost precludes many payloads and missions
- Precludes realization of aerospace force vision

Commercial Launch



- No impact on RDT&E budget
- Potential economies of scale
- CRAFT-like model

- Military future not in Air Force control
- Commercial vehicles not optimal for military operations
- Potential for US to lose predominance in space
- Precludes realization of aerospace force vision

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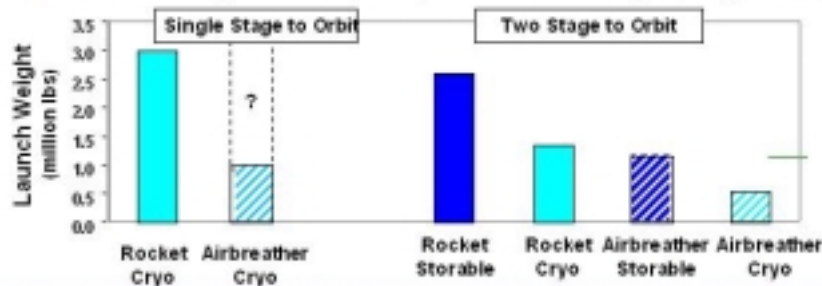
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Assured Space Access: Conclusions

- Military access to space is the compelling rationale for hypersonics
 - Potential for aircraft-like operations to/from space
- Both air breathing and rocket solutions are potentially viable
 - Air breathing higher risk with revolutionary potential
 - Rocket lower risk with evolutionary potential
- Propulsion technology is the key performance/cost/risk driver
 - Air breathing solutions offer 2X smaller size and some cost reduction
- Air breathing solutions, using known technologies, require staging



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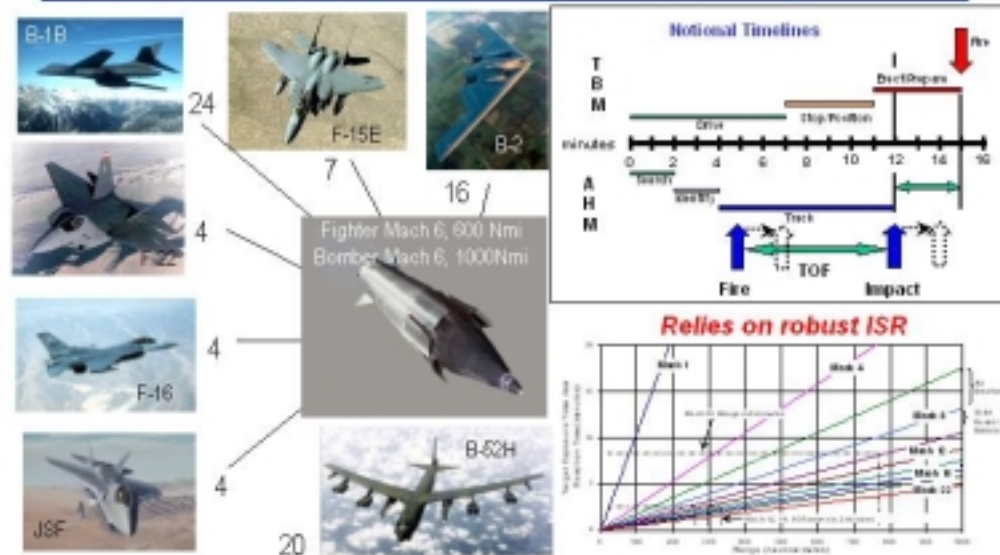
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Air Breathing Hypersonic Missile: Ops Concept



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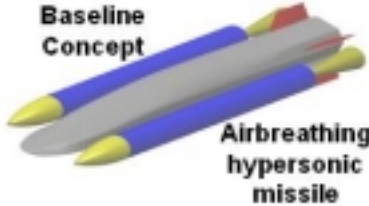
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High Speed Missile: Alternatives

Baseline Concept



Airbreathing hypersonic missile

PRO

- Quick reaction against fleeting targets
- Sized for tactical aircraft
- Possible long range AAM or SEAD
- Penetrator derivative
- Increased survivability

CON

- Seeker complexity or ISR reliance
- Limited target set, simple countermeasures
- Limited load out (configuration dependent)
- Low warhead mass fraction/range trade
- Uncertainty in size of target set



Rocket motor hypersonic missile

- Relatively low risk and near term
- Quick reaction against fleeting targets
- Sized for tactical aircraft
- Possible long range AAM or SEAD
- Penetrator derivative
- Increased survivability

- Seeker complexity or ISR reliance
- Uncertainty in size of target set
- Low warhead mass fraction/range trade
- Limited target set, simple countermeasures

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High Speed Missile: Alternatives

Directed Energy Weapon



PRO

- Equivalent Mach-1-million weapon Large magazine
- Limited collateral effects

CON

- Clouds, target hardness
- Treaty implications
- Requires large investment
- Vulnerability
- Limited range



Information Warfare

- Low investment
- Operational flexibility

- Uncertain effects
- Severe intelligence dependence



Manned Penetrator

- Current CONOPS
- Low cost solution
- Flexible

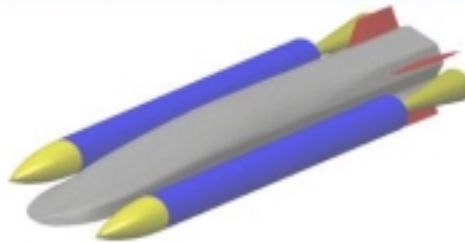
- Risks aircrew and/or platform
- More platforms required

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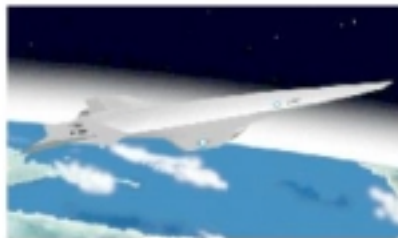
Airbreathing Hypersonic Missile: Conclusions



- Both Airbreathing and Rocket Propulsion Alternatives Are Viable
 - Rigorous System Level Studies/Analysis Will Identify Best Approach
- Airbreathing Missile Propulsion Technology Development Will Reduce Space Access Propulsion Risk
 - Nominal 60-80% Commonality (On Technology Basis)
 - Small Size Results in Affordable Approach
- Most of the hypersonic missile utility will depend on robust ISR

Flight Demonstration Required To Verify Propulsion Performance and Cost

Long Range Aircraft



- Long range future strike aircraft is derived from two-stage, air-breathing RLV (1st, 2nd, or both stages)
- Capabilities:
 - Prompt global attack when forward basing is denied
 - High survivability (speed + stealth + altitude + standoff + maneuver + self defense)
 - Rapid global mobility



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Long Range Aircraft: Alternatives

Baseline Concept



**Rocket motor
hypersonic
missile**

PRO

- Reusable
- High speed global reach
- Survivability

- Relatively low risk and near term
- Quick reaction against fleeting targets
- Sized for tactical aircraft
- Possible long range AAM or SEAD
- Penetrator derivative

CON

- New development and infrastructure
- Limited real time targeting capability
- No defined ConOps

- Seeker complexity or ISR reliance
- Uncertainty in size of target set
- Low w/h mass fraction/range trade
- Limited target set, simple countermeasures

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Long Range Aircraft: Alternatives

Baseline Concept



**Rocket motor
hypersonic
missile**

PRO

- Reusable
- High speed global reach
- Survivability

- Relatively low risk and near term
- Quick reaction against fleeting targets
- Sized for tactical aircraft
- Possible long range AAM or SEAD
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CON

- New development and infrastructure
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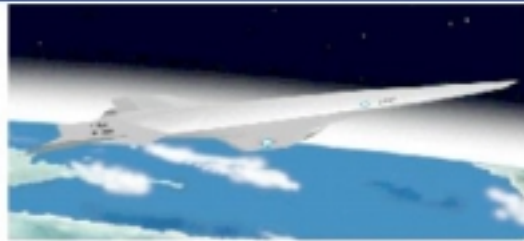
- Seeker complexity or ISR reliance
- Uncertainty in size of target set
- Low w/h mass fraction/range trade
- Limited target set, simple countermeasures

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Long Range Aircraft : Conclusions



- **Marginal military utility of this system over other alternatives has not been established. Air breathing propulsion is required for this mission**
 - Rockets not compatible with aircraft operations
 - Access to space first stage provides vehicle or technology basis depending on concept selected
- **Air breathing technology selection drives system concept**
 - Turbine based cycles effective to mach 4
 - Storable ramjet/scramjet fuels effective to mach 8
 - Cryogenic ramjet/scramjet fuels enable mach 20+ with potential for global unrefueled range

Plasma Application: Conclusions

- **High risk – high pay-off plasma technologies offer potential to radically change hypersonic aircraft and their application**
 - MHD power extraction offers potential for significant on-board power for beam weapons and other uses
 - Aerodynamic flow modification might lead to significant performance gains
- **There is a small marginal cost (6.1, 6.2) for determining whether or not these technologies will work**





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Concept Recommendations

- Develop mission and system concepts to meet the Air Force vision (AFSPACECOM)
 - CSAF review and approve
 - Publish appropriate statement(s) of operational requirements
- Assign either SMC or ASC clear leadership responsibility for air breathing hypersonics system engineering with the other supporting
- Develop an overall hypersonics roadmap and identify and schedule critical enabling technical decisions (SAF/AQ)
 - Use SAB recommended program as a guide

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Hypersonic Investment Strategy - Our Logic

- USAF is unprepared to decide the critical issues that will define future space access/operations architecture
 - Many opinions, little data
 - High risk of ill-informed decision
- Recommended investment program focuses on critical data needs for USAF decisions on an assumed 2025 system IOC
 - Go - No go
 - Preferred concept selection
 - Technology content
- Investment program must integrate other agency efforts
 - NASA planning/conducting multi-billion dollar access to space concept & technology exploration (but against different goals and requirements)
 - DARPA ARRMD program provides hydrocarbon engine data
- Investment program should consider near term funding reality
 - FY03-04 earliest practical opportunity for significant new effort

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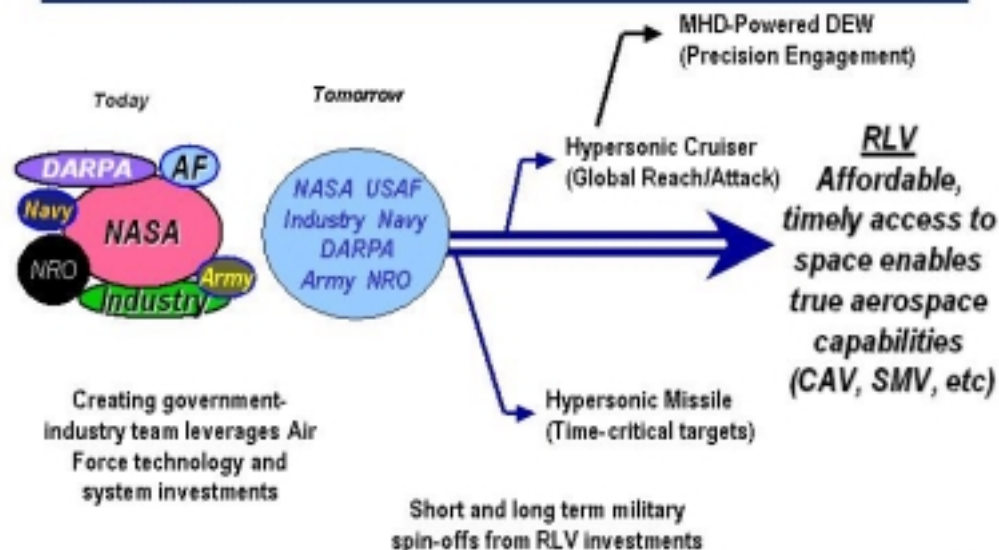
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Investment Approach



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Hypersonics Investment Planning Emphasizes Decision Readiness

- Rigorous system level studies and analyses are required to support key technical decisions
 - Expendable vs. reusable launch vehicle?
 - Airbreathing vs. Rocket propulsion?
 - Vertical vs. Horizontal takeoff?
 - Single vs. Two stage, staging/cruise mach number?
 - Cryogenic vs. Storable propellants?
 - Turn time/sortie rate/basing requirements?
 - Composite vs. Metallic tanks, ceramic vs. Metallic TPS?
 - Etc?
- Technology development and demonstration will provide data for system analyses/trades/decisions
 - Data based critical decisions reduce downstream cost and risk for decades to follow

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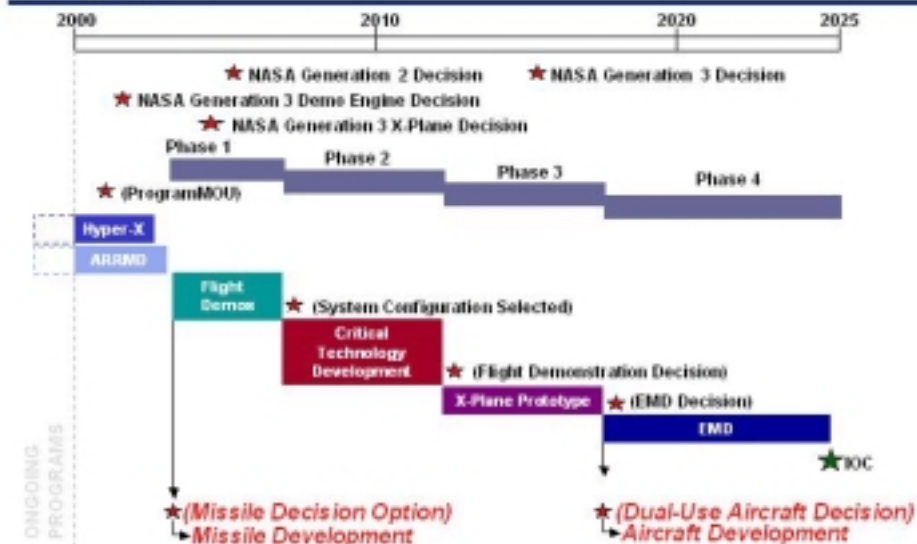
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Long Term Roadmap

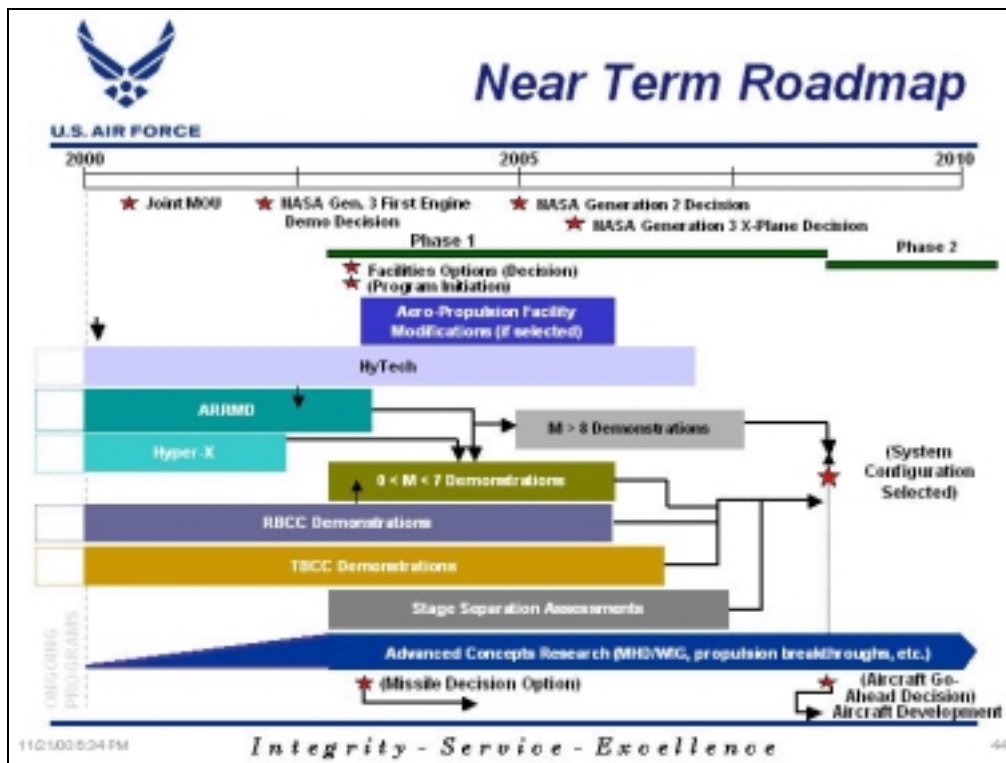
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Recommended Annual Funding (\$M)

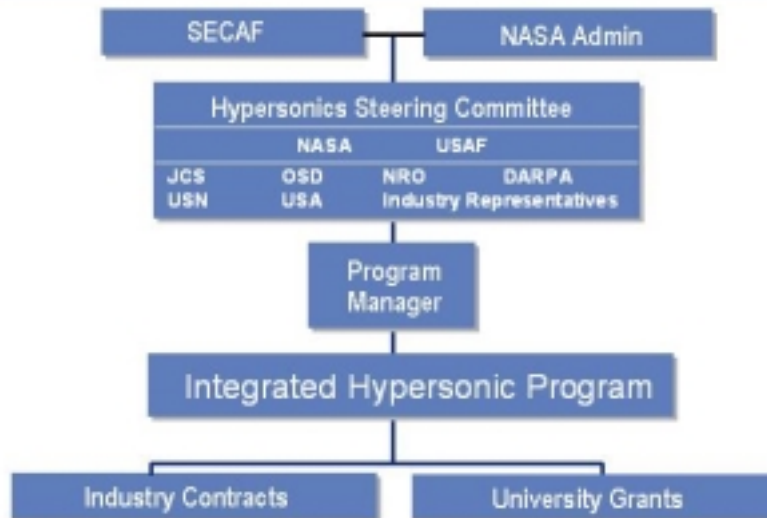
	Phase 1				Phase 2	Phase 3	Phase 4
	FY01	FY02	FY03	FY04-06	FY07-11	FY12-17	FY18-25
USAF	6	6	18	30-40	150-200	300-400	400-500
NASA	30	30	30	30-40	150-200	300-400	400-500
Total	36	36	48	60-80	300-400	600-800	800-1000
Others					TBD		

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Initial Integrated Hypersonics Program Organization



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Program Recommendations

- Join with NASA in an integrated program focused on answering the key technical questions on air breathing hypersonics (SECAF)
 - Include other service and industry participation
- Insert a funding wedge starting in 03-04 into the 02 budget submission for a robust program that supports SPACECOM needs (SAF/AQ)
- Form a hypersonic technology team during FY01/02 to engage technically with the AF HyTech, the DARPA ARRMD, and the NASA Hyper-X flight demonstration teams (SAF/AQ)
 - Develop lessons learned and understanding
 - Offer in-house support as possible
- Continue to fund, at current levels, HYTECH and selected hypersonic initiatives consistent with FY01-02 funding availability (SAF/AQ)
 - Projects should be realigned to support downstream critical decisions to the extent possible

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The Transformation of Air Power

	New Capabilities						
	Longer Range	Higher Speed	More Lethal Weapon	New Sensors/ Equip.	Improved Interoperability	Reduced Detectability	New Environment
1980 – 1990		After Burner Turbo Engines	UAVs Mach 3 Bombers	Navigation Datalink			
1990 – 2000	Stealth Fuel Efficiency	Higher Power Turbo Engines	Standoff Weapons	Threat Detection		Reduced Detectability (IR/ECV)	Global Vigilance Reach and Power
2000 – 2010	Stealth Catalytic A/C	Radial Engines Catalytic Engines	Multiple MG	Radio-Data Link Paging Rate	Aircraft Radio		Global Vigilance Reach and Power
2010 – 2020	Low Altitude Stealth	Proton H2 O2 Fuel	Power Turbine	Search Radar Gyro Bombing	Global Vigilance Reach and Power		Global Vigilance Reach and Power
2020 – 2030	High Altitude Stealth	Proton H2 O2 Fuel	Power Turbine	Search Radar Gyro Bombing	Global Vigilance Reach and Power		Global Vigilance Reach and Power
2030 – 2040	High Altitude Stealth	Proton H2 O2 Fuel	Power Turbine	Search Radar Gyro Bombing	Global Vigilance Reach and Power		Global Vigilance Reach and Power
2040 – 2050	High Altitude Stealth	Proton H2 O2 Fuel	Power Turbine	Search Radar Gyro Bombing	Global Vigilance Reach and Power		Global Vigilance Reach and Power
2050 – 2060	High Altitude Stealth	Proton H2 O2 Fuel	Power Turbine	Search Radar Gyro Bombing	Global Vigilance Reach and Power		Global Vigilance Reach and Power
2060 – 2070	High Altitude Stealth	Proton H2 O2 Fuel	Power Turbine	Search Radar Gyro Bombing	Global Vigilance Reach and Power		Global Vigilance Reach and Power
2070 – 2080	High Altitude Stealth	Proton H2 O2 Fuel	Power Turbine	Search Radar Gyro Bombing	Global Vigilance Reach and Power		Global Vigilance Reach and Power
2080 – 2090	High Altitude Stealth	Proton H2 O2 Fuel	Power Turbine	Search Radar Gyro Bombing	Global Vigilance Reach and Power		Global Vigilance Reach and Power
2090 – 2100	High Altitude Stealth	Proton H2 O2 Fuel	Power Turbine	Search Radar Gyro Bombing	Global Vigilance Reach and Power		Global Vigilance Reach and Power



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What Will Be The Next Transformation?

	New Capabilities						
	Longer Range	Higher Speed	More Lethal Weapon	New Sensors/ Equip.	Improved Interop.	Reduced Detectability	New Environment
2000 - 2010	Scramjet Hypersonic	Turbojet/ Scramjet	UAV Weapons	Intermittent AirSpace Arch	GB JBI	"Active" Stealth	Global Vigilance Reach and Power
2010 - 2020	MHD-Tailored Hypersonics	MHD Flow Control Propulsion	Low-Altitude Weapons	"Seamless" AirSpace Arch	"Seamless" AirSpace Ops	Invincible Air Vehicle	Space Problems Info Ops
2020 - 2030	Commercial Hypersonics	Propulsion Breakthrough	Beams from Space	Pervasive Intel			Global Control from Space

Hypersonics and hypersonic related technologies offer the potential for revolutionizing aerospace warfare

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Summary Recommendations

- **Clarify the Vision by defining the specific Air Force Mission Needs**
- **Start with the SAB recommended program and modify it to meet the defined mission needs**
- **In the meantime, continue on-going efforts to answer the key technical questions**

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USD (A&T)/DSB	Defense Science Board
DARPA	Defense Advanced Research Projects Agency
	- Tactical Technology Office
DIA	Defense Intelligence Agency
	- MSC
DISA	Defense Information Systems Agency
BMDO	Ballistic Missile Defense Organization

Other Air Force Organizations

AC2ISRC	Aerospace Command, Control, Intelligence, Surveillance, and Reconnaissance Center
ACC	Air Combat Command
- CC	- Commander, Air Combat Command
- DRM	- Directorate of Requirements
- 366th Wing	- 366th Wing at Mountain Home Air Force Base
AETC	Air Education and Training Command
- AU	- Air University
AFMC	Air Force Materiel Command
- CC	- Commander, Air Force Materiel Command
- EN	- Directorate of Engineering and Technical Management
- AFRL	- Air Force Research Laboratory
- SMC	- Space and Missile Systems Center
- ESC	- Electronic Systems Center
- ASC	- Aeronautics Systems Center
- HSC	- Human Systems Center
- AFOSR	- Air Force Office of Scientific Research
AFOTEC	Air Force Operational Test and Evaluation Center
AFSAA	Air Force Studies and Analyses Agency
AFSOC	Air Force Special Operations Command
AFSPC	Air Force Space Command
- DRSV	- Directorate for Requirements
AIA	Air Intelligence Agency
AMC	Air Mobility Command
NAIC	National Air Intelligence Center
NGB/CF	National Guard Bureau
PACAF	Pacific Air Forces
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USAFE	US Air Forces in Europe

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- Dept. of Mechanical and Aerospace Engineering

University of Maryland

- Dept. of Aerospace Engineering

US Army Space and Missile Defense Command

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